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Geology of the Franklin D. Roosevelt Reservoir Shoreline:

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Glacial Geology, Terraces, Landslides, and Lineaments

Prepared by
Grand Coulee Power Office

United States Department of the Interior
Bureau of Reclamation

DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PACIFIC NORTHWEST REGION

GEOLOGY OF THE FRANKLIN D. ROOSEVELT RESERVOIR SHORELINE: GLACIAL GEOLOGY, TERRACES, LANDSLIDES, AND LINEAMENTS

GRAND COULEE POWER OFFICE
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NATIONAL PARK SERVICE
WATER RESOURCES DIVISION
FORT COLLINS, COLORADO
RESOURCE ROOM PROPERTY

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INTRODUCTION

General Statement

Purpose

Surficial deposits along the flooded valleys of the Columbia River and its tributaries from Grand coulee Dam to Canada were studied during the 1983 to 1985 field seasons as part of the shoreline investigation studies of 151-mile (242 km) long Lake Roosevelt. Minor manuscript updates and review of maps were completed in 1994. An understanding of the geologic events that affected the Columbia River valley and surrounding area is basic to intelligently evaluating the nature of the sediments along Lake Roosevelt and their stability. An inventory of geologic features and unconsolidated sediments along the 600 miles (960 km) of Lake Roosevelt shoreline was made to assist U.S. Bureau of Reclamation (Reclamation) geologists and others in making decisions concerning land use, slope stability, and slope stabilization. In addition, potential problem areas and areas where more work or knowledge is needed are identified. The availability of a general report such as this can also act as an introduction to Reclamation personnel to the origin and characteristics of the abundant unconsolidated sediments along the reservoir and to some of their associated geological problems.

Products

Geologic Maps. The primary means for summarizing the distribution of geologic materials and features along Lake Roosevelt is through the use of geologic maps. Such maps provide much of the necessary geologic data from which models can be developed that describe the sequence and nature of geologic events which have affected and/or may affect an area. Through this application the maps help to understand the conditions that influence areas where slope failure occurs and to identify similar areas where future slope failure may occur.

All of the deposits above 1290 feet (390 m) elevation (full pool level of Lake Roosevelt) were mapped on topographic quadrangles (Figure 1) at a scale of 1:24,000 (1-inch = 2000 feet). Such a scale is useful for the reconnaissance investigation reported here and also to place an area that is under detailed investigation into its more general geologic setting. However, the 1:24,000 scale does not provide sufficient map space to adequately show small outcrops, areas along the reservoir where rapid material changes occur, or areas where an abundance of features such as springs or landslide scars occur in close proximity. In selected areas, the position of landslide scars and areas of riprap are exaggerated in order to show them on the maps.

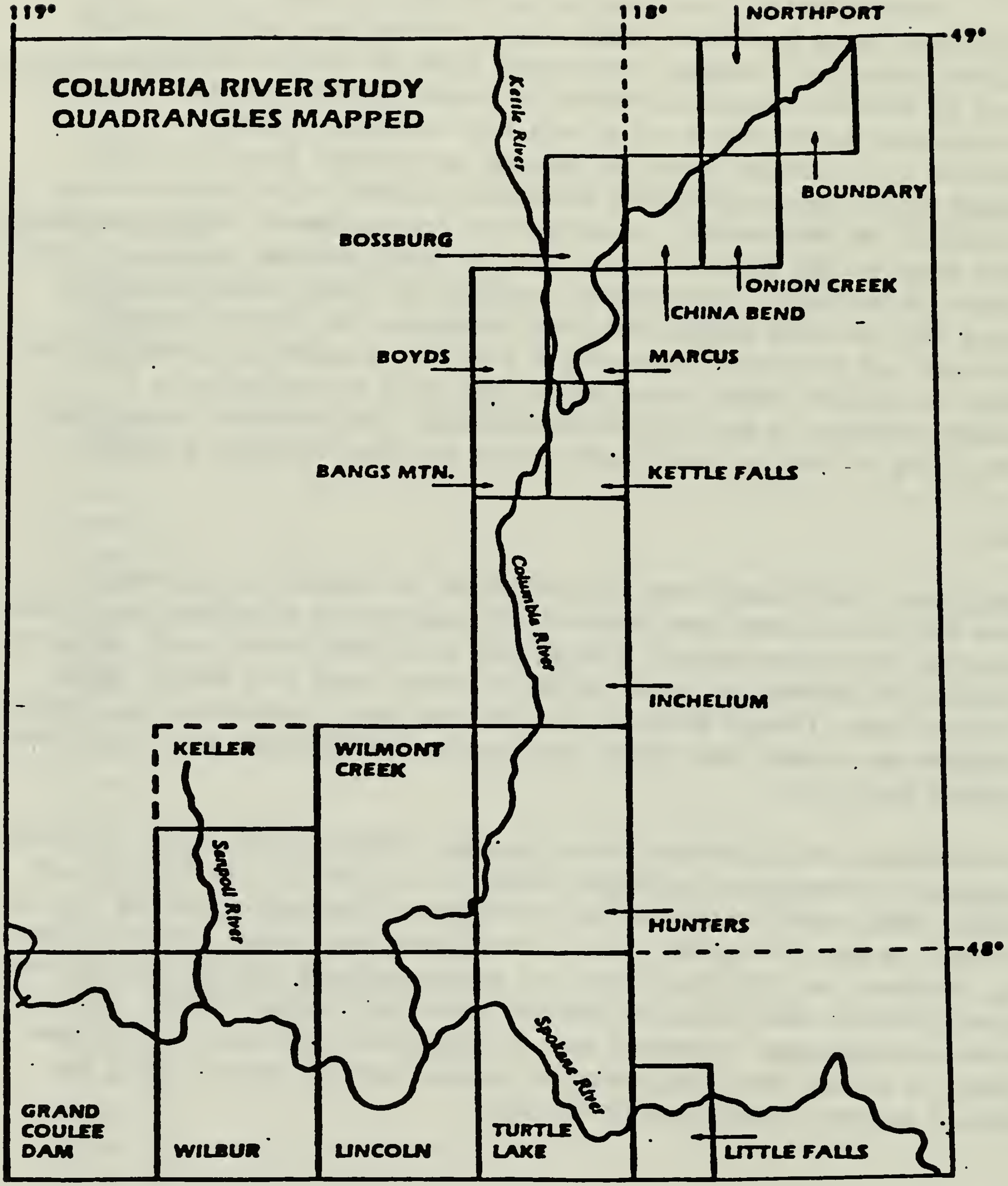


FIGURE 1 - Map of Lake Roosevelt Area and Topographic Map Coverage

In addition to the types and distribution of unconsolidated sediments, bedrock lithology, lineaments, springs, landslide scars, and many other features are also shown on the maps.

Using Reclamation topographic sheets 28 and 53 at a scale of approximately 1:4800 as base maps, detailed geologic maps of these selected areas were made. The amount of detail and accuracy is greatly improved.

Terrace and Slope Classification. Terraces and slopes immediately adjacent to the reservoir were classified using an alphanumerical system that provides basic data concerning whether landslides are present at a given site, the type of landslide present, and what critical slope instability factors occur at that location. The information determined for specific locations along the reservoir edge are provided on the terrace classification maps accompanying this report.

Photostratigraphy. Examples of the exposed stratigraphy along the reservoir is provided on clear plastic overlays of 8- by 10-inch black and white photographs. The photographs, overlays, and index maps of photo locations are provided as a separate package accompanying this report. The resulting compilation of photographs provides a rapid, visual reference of the stratigraphy and the appearance of the reservoir edge at numerous sites.

Methods

Previous Work

A review of published literature and maps was made prior to starting investigations in 1983. A search for unpublished materials, including theses, uncovered a number of reports on local geology along the reservoir. Many reports and publications pertinent to Lake Roosevelt are listed in the bibliography. Most of these reports are bedrock oriented but were useful in confirming the location and geologic characteristics of bedrock and faults. Many more structures and possible structures were located using airphotos and topographic maps than are reported in the literature or could be shown on the 1:24,000 scale maps.

All of the reports, except for Jones and others (1961), Flint and Irwin (1939), and Atwater, (1986) treat the unconsolidated materials very superficially or are of a reconnaissance nature and present a broad picture with very little detailed discussion of specific sites. General papers by Flint (1936 and 1937), Richmond and others (1965), Richmond (1986), and Waitt and Thorsen (1984) are useful in providing models to help explain the origin and location of various sediments. Although bedrock maps usually consider unconsolidated materials together as an undifferentiated unit, often such maps give suspected ice margins or other information useful to those concerned about the sediments. Ice margins in particular place important restrictions on the distribution of certain types of sediments.

Airphoto Interpretation

Airphotos are the single most useful tool in producing reconnaissance scale geologic maps and were used extensively in this study. Color infrared (CIR) airphotos at a scale of 1:24,000 flown in June 1984 were extremely valuable in making preliminary photogeologic maps and in modifying contacts between geologic materials after field investigations were completed. Airphotos provide a view of surface features and topography not available to the ground observer. Thus, many obscure but potentially significant features such as old landslide scars and lineaments that would otherwise go unrecognized can be identified by using airphotos.

Reclamation black and white airphotos, taken in May of 1974, at a scale of about 1:29,000, were also available and provided some information about areas between the high water level of 1290 feet (390 m) and 1170 feet (360 m), the water level at the time of the flight.

Geologic contacts and other information obtained from airphotos were plotted on all U.S. Geological Survey topographic maps that touch the reservoir (Figure 1). Where maps at 1:24,000 scale were not available, smaller scale (1:62,500) maps were enlarged to a 1:24,000 scale. Forty maps (1:24,000 scale) cover the entire reservoir and sufficient area back from the edge to provide an overview of geologic conditions at any given site along the reservoir. The maps used in this study, their year of issue, as well as more recent editions are listed in Table 1.

Landsat (1:1,000,000 scale) and high altitude U-23 images (1:64,650 approximate scale) were used in identifying large scale lineaments that extend beyond the area shown on the large scale CIR and black and white photographs and in producing preliminary geologic contacts in areas not covered by the large scale photographs.

Field Studies

A 14-foot outboard boat was used to gain access to the numerous exposures of surficial materials along the reservoir edge and a field vehicle was used to facilitate outcrop examinations along the many roads in the Columbia and Spokane valleys. Thus, some ground truth was established and used to verify or modify contacts determined by airphoto studies. The resulting geologic maps, although of a reconnaissance nature, contain considerable detail and are the only maps available that delineate locations and types of unconsolidated materials present for the entire Lake Roosevelt area.

Finer sediment sizes were estimated by field classification or observing the behavior of the sediment in exposures. Clay and fine silts are more cohesive and tend to hold vertical slopes and often produce perched ground-water conditions. Sand layers are permeable, less cohesive, and often show ripple lamination structures. Loosened sand is often redistributed by wind into sand ripples on the exposed surface.

Table 1

Topographic Base Maps

Original Base Map	Date	Updated Base Map	Date
15 Minute Series		**7.5 Minute Series**	
Grand Coulee Dam (NW)	1948	Grand Coulee	1989
Grand Coulee Dam (NE)	1948	Mica Mountain	1989
Grand Coulee Dam (SW)	1948	Jack Woods Butte	1989
Grand Coulee Dam (SE)	1948	Broadax Draw	1989
Wilbur (NW)	1948	Keller Ferry	1989
Wilbur (NE)	1948	Whitestone Rock	1989
Wilbur (SE)	1948	Creston	1989
Wilbur (SW)	1948	Wilbur	1989
Keller	1952	Keller	1989
Lincoln (NW)	1948	Johnny George Mtn	1985
Lincoln (SW)	1948	Lincoln	1985
Lincoln (SE)	1948	Olsen Canyon	1985
Lincoln (NE)	1948	Fort Spokane	1985
Turtle Lake (NE)	1948	Turtle Lake	1985
Turtle Lake (NW)	1948	McCoy Lake	1985
Turtle Lake (SW)	1948	Inkster Lake	1985
Turtle Lake (SE)	1948	Benjamin Lake	1985
Wilmont Creek (SW)	1948	Ninemile Flat	1985
Wilmont Creek (SE)	1948	Miller Mountain	1985
Wilmont Creek (NE)	1948	Kewa	1985
Wilmont Creek (NW)	1948	Gold Mountain	1985
Hunters (SW)	1948	Hunters	1985
Hunters (NW)	1948	Cedonia	1985
Hunters (NE)	1948	Blackhorse Canyon	1985
Hunters (SE)	1948	Adams Mountain	1985
Inchelium (SW)	1950	Inchelium	1985
Inchelium (NW)	1950	Rice	1985
Inchelium (NE)	1950	Wellington Peak	1985
Inchelium (SE)	1950	Kentry Ridge	1985
Bangs Mountain	1969	Bangs Mountain	1982
Kettle Falls	1969	Kettle Falls	--
Marcus	1969	Marcus	1979
Boyds	1969	Boyds	--
Bossburg	1969	Bossburg	--
China Bend	1969	China Bend	--
Onion Creek	1969	Onion Creek	1982
Northport	1969	Northport	1982
Boundary	1952	Boundary	1982

Well Logs

Logs of wells drilled between 1973 and 1984, obtained from the Washington State Department of Natural Resources (DNR), were examined after the field mapping was completed. Wells drilled prior to 1973 were not required to be filed with the DNR. The number of registered wells on each 7.5 minute quadrangle touching Lake Roosevelt varied from none in Wilmont Creek NE to 24 in the Marcus quadrangle. Available well logs cluster close to the reservoir edge. A tabulation of the number of available well logs for each quadrangle is shown in Table 2.

The well logs are of mixed quality and usefulness. However, a number of them were excellent and helped verify or improve greatly the stratigraphic designations shown on the geologic maps. Additional information could be acquired by visiting with landowners in the area and learning more about the materials that their domestic and irrigation wells penetrate.

Mapping Units

The system of symbols devised for the geologic maps is an attempt to include as much information as possible without making the use of the map unduly complicated. Specific information that has to be looked up in accompanying reports is more likely to be ignored than information that is readily available on a map. Colluvium was not included as a unit partly because of the difficulty of showing it at a 1:24,000 scale. Also, if it were used, some stratigraphic information would be obscured or lost.

The map symbols describing geologic materials have a threefold arrangement. The first letter or letters designate(s) the geologic era or period (Precambrian - pC; Paleozoic - P; Quaternary - Q; etc.) the second lithology (Tcr = Tertiary age Columbia River basalt; Cl = Cambrian age limestone; etc); and the third sediment texture.

The second symbol, following only the Quaternary age material (Q), indicates the geologic process or environment that controlled the type of sediment that accumulated. The seven major categories are:

1. e = eolian
2. o = outwash
3. f = flood
4. l = lacustrine
5. d = glacial or ice-caused drift
6. t = till
7. a = alluvial or stream
8. s = landslide or slide
9. r = artificial fill or riprap

Table 2
Number of Well Logs from The Department of Natural Resources for each 7½" Quadrangle Touching Lake Roosevelt

Quadrangle	Well Logs Obtained
Boundary	1
Northport	6
Onion Creek	3
China Bend	3
Bossburg	1
Marcus	24
Boyds	0
Kettle Falls	14
Bangs Mt.	1
Rice	10
Inchelium	12
Cedonia	10
Hunters	1
Kewa	0
Nine Mile Flat	0
Miller Mountain	2
Johnny George Mountain	0
Fort Spokane	11
Lincoln	16
Olsen Canyon	3
Keller Ferry	6
Whitestone Rock	5
Creston	2
Keller	2
Grand Coulee	5
Mica Mountain	4
McCoy Lake	2
Jakster Lake	3
Benjamin Lake	0

In addition, some categories are further broken down. For example, the symbol "d" that stands for glacial or ice-generated drift undifferentiated, can be replaced by "t" (till) or "o" (outwash). Till deposits are further broken down to indicate the relative age of the materials with t_1 being late Wisconsin, t_2 being Pre-Wisconsin, younger, and t_3 being Pre-Wisconsin, older. Slide debris (s) can be further categorized into s_1 (slump-flow deposits), s_2 (rockslide deposits), or s_3 (talus - debris whose origin was probably through less massive slope failures).

The third symbol in the tripartite designation provides textural information. Particle size estimates were made using the Unified Soil Classification System (Table 3) as a standard. Gravel was designated as pebble (g_1), cobble (g_2), boulder (g_3), or mixed size gravel with many sizes represented (g_4). Other categories include sand (s); silt (m); clay (c); and clay and/or silt interbedded in sand (z); or undifferentiated (u).

Thus, a symbol such at Qt_1g_2c designates a Quaternary age (late Wisconsin) till composed of cobble-size gravel in a clay-size matrix. A symbol such as $Qt_1g_2c/og_1/ls$ would designate the same till unit over an outwash gravel of pebble size which in turn overlies a lacustrine sand. Other symbols depicted on the geologic maps are used to identify special landforms and features of geologic or engineering interest.

GLACIAL GEOLOGY

Introduction

During the Pleistocene, an ice sheet grew to large proportions, covering most of British Columbia. Ice advanced across the international boundary and moved farthest south in the large south-trending structural valleys in the northern Rocky Mountains. Each major tongue or lobe is named for the valley it occupied. The ice lobes in northeastern Washington, from west to east, include the Okanogan, San Poil, Columbia, Colville, Little Spokane, and Pend Oreille lobes. Pertinent to Lake Roosevelt are the effects of the Okanogan, San Poil, and Columbia Valley lobes. Ice thickened in the valleys as the advance progressed and eventually coalesced over drainage divides producing a continuous ice cover over northeastern Washington except for a few peaks (nunataks) that projected above the ice sheet surface. The ice surface sloped from over 7000 feet (2135 m) elevation near the international border where the ice was about 6000 feet (1830 m) thick to about 1300 feet (400 m) elevation some 75 miles (120 km) to the south where the ice terminated (Figure 2).

Most of the sedimentary deposits in the Lake Roosevelt area are late Wisconsin in age. Thus, the late Wisconsin events are easiest to decipher and most critical to understanding the landforms and sediments along Lake Roosevelt. The older glaciations are assumed to have produced similar features except that the older advances were more extensive than the youngest advance and their depositional record is poorly preserved.

During late Wisconsin time (about 15,000 years ago) or perhaps earlier, the Columbia lobe advanced to its maximum position (Lamb Draw or Rothlisburg advance) near the Spokane-Columbia confluence. It's terminus ended either in a shallow lake or subaerially which indicates that the Okanogan lobe had not yet sufficiently blocked the lower Columbia Valley to produce a high level glacial lake. The Lamb Draw moraines overlie a pebbly flood gravel which indicates that the Purcell Trench lobe in northern Idaho was in place and catastrophic floods from Lake Missoula were being generated before a deep Lake Columbia was in place.

Advance of the Okanogan lobe into Grand Coulee substantially increased the glacial lake depth and produced rapid calving and establishment of a new ice front a few miles to the north of Lamb Draw near Castle Rock Creek about 13,000 - 15,000 years ago. Episodic but rapid retreat, equilibrium at the Hunters ice front (Figure 3), at least one readvance of the ice in the Kettle Falls-Marcus area (Figure 4), and at least two major changes in the level of glacial Lake Columbia created a series of lake terraces, kame terraces, kame deltas, lateral moraines, and other glacial features along the upper Columbia River valley. The Okanogan glacier had retreated north of the Columbia Valley by the time the Glacier Peak (11,200 years B.P.) and Mount St. Helens J. (11,000 - 12,000 years ago) volcanic ash deposits were subaerially deposited on higer, more southern terraces in the Okanogan Valley but a low standing lake continued to occupy the Columbia Valley below 1400 feet. In the Colville and Pend Oreille Valleys to the east ice had at least retreated as far north as 48° 30' (near Colville) by 11,000 - 12,000 years ago (Corrora and others 1994). Presumably ice in the Columbia Valley was at or north of an equivalent position 11,000 to 12,000 years ago. A more detailed discussion of the glacial chronology and stratigraphy is presented in Appendix A.

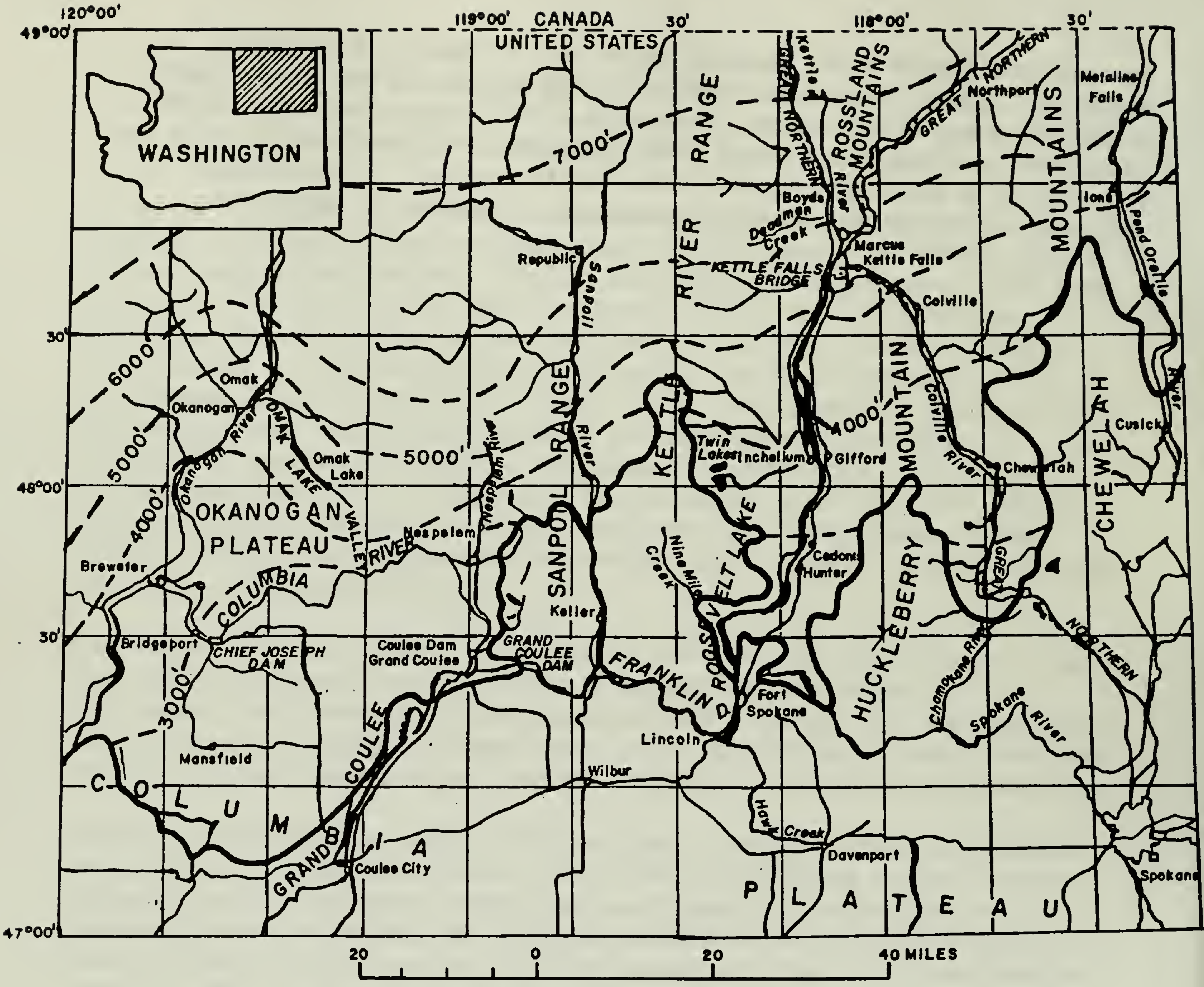


FIGURE 2 - Late Wisconsin ice extent and thickness. Thousand foot contours on ice surface. Base map from Jones and others (1961), ice borders modified from Richmond and others (1965), and Waitt and Thorsen (1984), and ice contours modified from Richmond and others (1965).

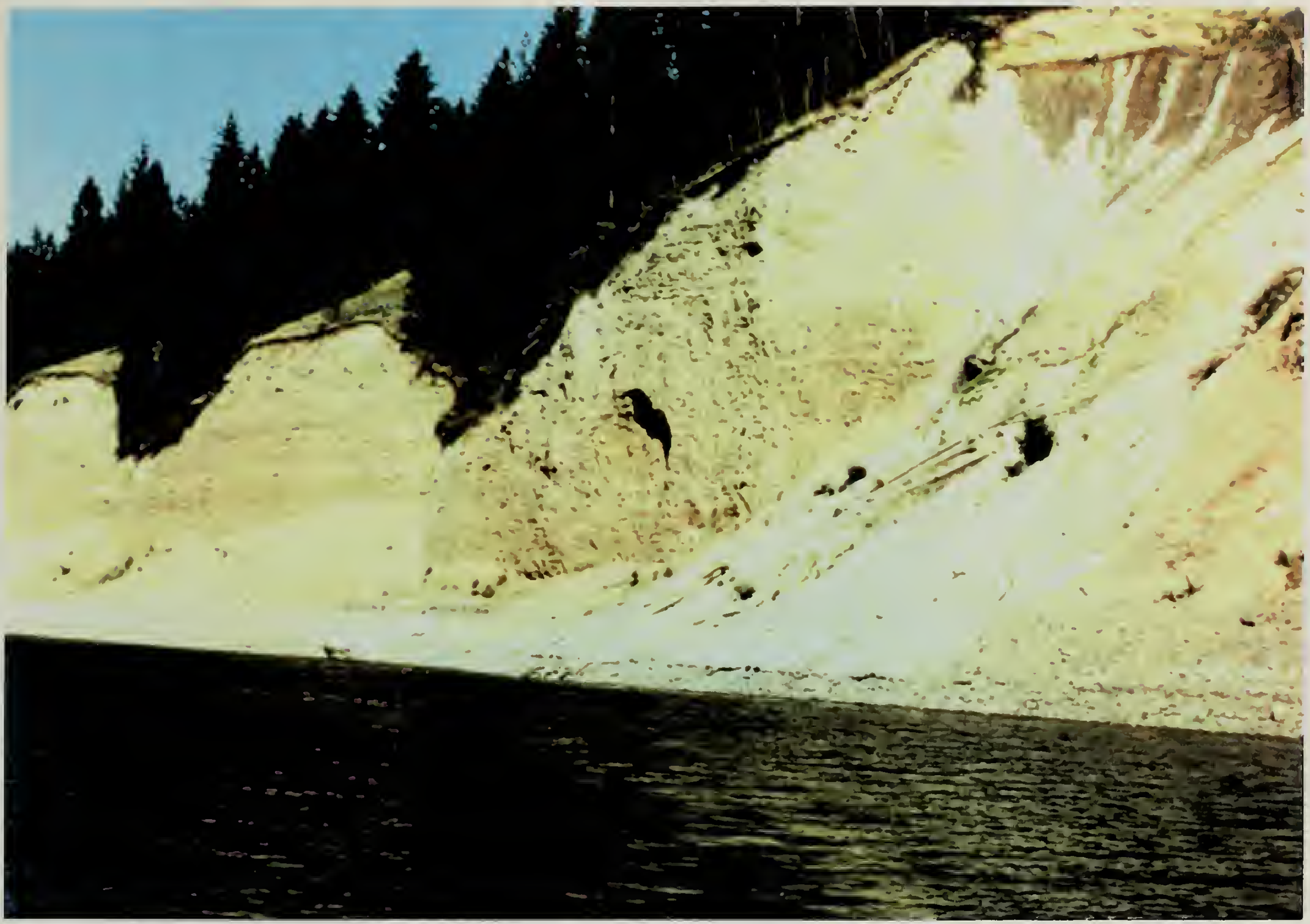


Figure 3 - Hunters ice position (W3). Till and kame delta deposits overlain by Lake Columbia III sediments; Photo taken on 7/2/85

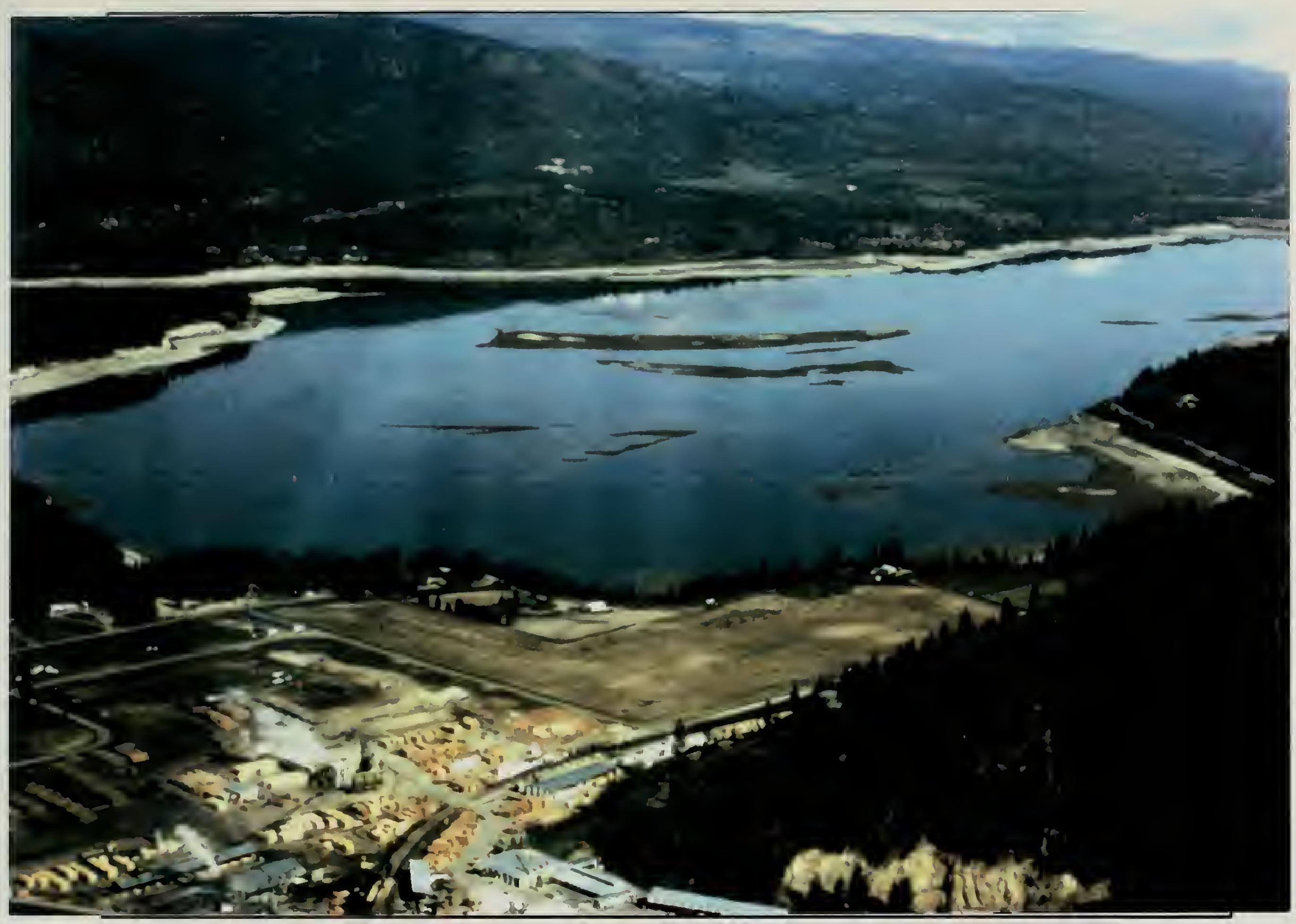


Figure 4 - Mission Bay ice margin. Ice contact position of the Kettle Falls Advance (W4)

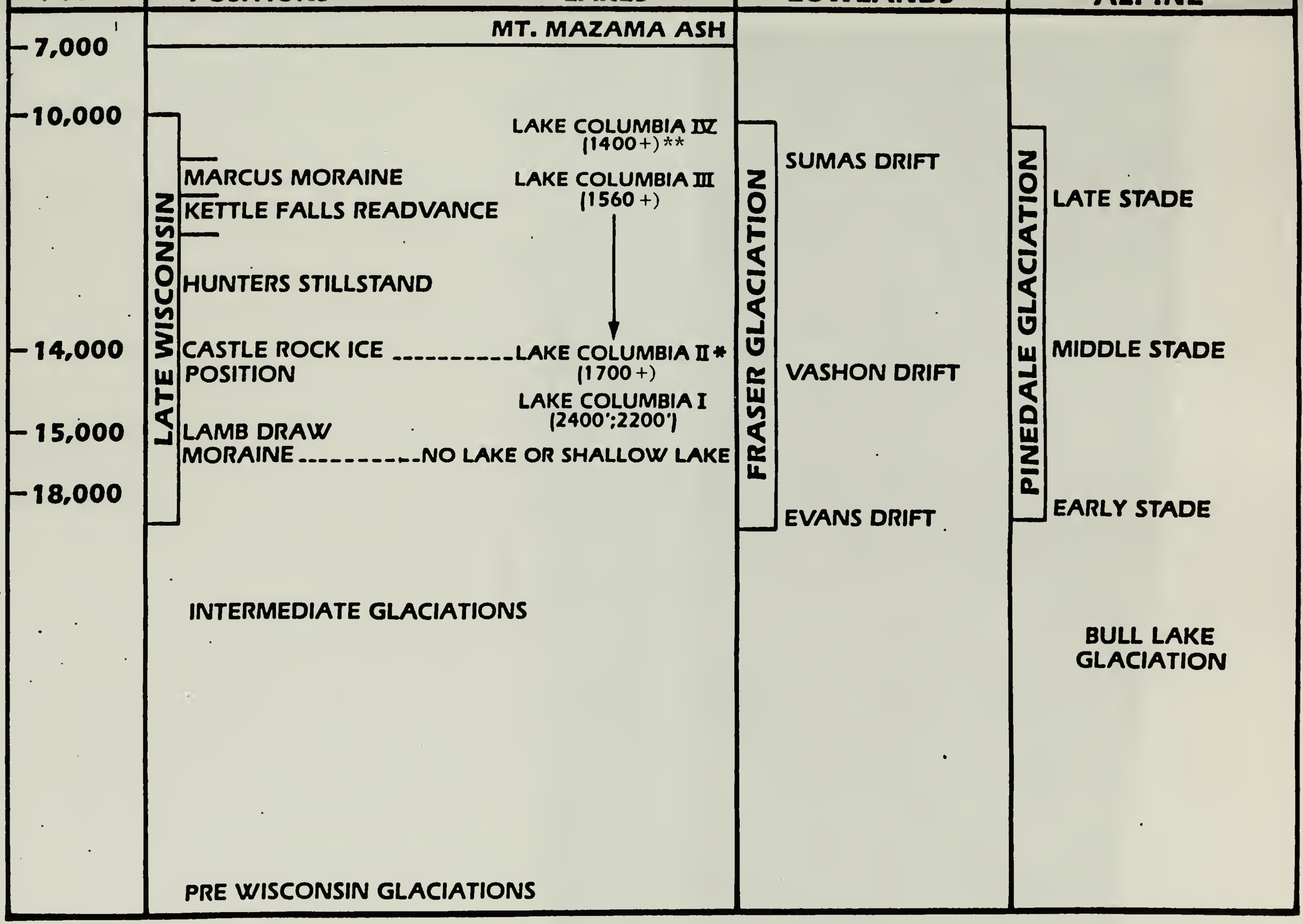
Terraces and Bars

A large number of flat or nearly flat surfaces underlain by Pleistocene age sediment occur along the margins of Lake Roosevelt in the Columbia River valley and its tributaries. Some of these surfaces are restricted in extent while others occur in widespread areas along the reservoir providing correlation keys to unraveling the Pleistocene history of the area (Figure 5). The bluffs along Lake Roosevelt expose the sedimentary materials that underlie these surfaces and these same exposures are also extremely important in slope stability studies along the reservoir. However, because these surfaces were formed by various combinations of sedimentary processes, different types of sedimentary materials with different engineering characteristics are present. Recognition of the variety of sedimentary materials, their stratigraphic sequence, and their geomorphic form and location can assist in more efficient categorization, classification, and prediction of slope behavior. Because the terraces and bars are composed almost entirely of late Wisconsin sediments, the following discussion concentrates on events occurring during this most recent glaciation. For a more detailed discussion see Appendix B.

Six prominent late Wisconsin lake and terrace levels are preserved along the margins of Lake Roosevelt. These are: (1) 2400 feet (735 m); (2) 2000 to 2200 feet (610-671 m); (3) 1680 to 1760 feet (510-535 m); (4) 1560 to 1600 feet (475-430 m); (5) 1400 to 1480 feet (430-455 m); and (6) 1320 to 1360 feet (405-420 m). Other prominent surfaces submerged beneath Lake Roosevelt's waters are inaccesible and were ignored in this study.

High level lakes must have occupied the Columbia River valley in pre-Wisconsin and earlier Wisconsin time before the upper end of the Grand Coulee was breached by the headward retreat of a large waterfall that migrated up the Grand Coulee to the Columbia River valley. Pre-late Wisconsin ice produced the 2500-foot (762 m) strandline in the Peter Dan Creek area and the nearby N ½ Section 33 in the Grand Coulee Dam NW quadrangle.

The highest late Wisconsin lake known is represented by the 2400-foot (732 m) Lake Columbia I strandline (Millikan 1981, p. 13) which is cut into late Wisconsin moraines in the Peter Dan Creek area. A lake at this level could account for similar elevation strandlines in the San Poil valley and for lacustrine sediments near Spokane and in the Little Spokane River basin much farther east. Further, the high level lake (2400 feet; 732 m) is only about 200 feet below the basalt plateau to the south suggesting that waterfall retreat had not reached the Columbia Valley by early late Wisconsin time. More widespread strandlines at the 2080- to 2307-foot (634-703 m) level (Figure 6) indicate a further reduction in lake level during the same glacial advance due to adjustments of the Okanogan ice against the east rock wall of Grand Coulee or breaching of the basalt rim by headward erosion of the Grand Coulee waterfall. The spectacular canyon of the upper Grand Coulee was mostly cut during pre-late Wisconsin time by the diverted waters of the Columbia River and by catastrophic glacial floods derived from glacial Lake Missoula in northwestern Montana (Figure 7). The final breaching into the Columbia River Valley likely occurred during early late Wisconsin time, perhaps after Lake Columbia II was eliminated.



* Mount St. Helens "S" ash

** Glacier Peak ash, 11,000-12,000 yr BP

FIGURE 5 - Tentative correlation chart of Quaternary events in the Columbia Valley and nearby region

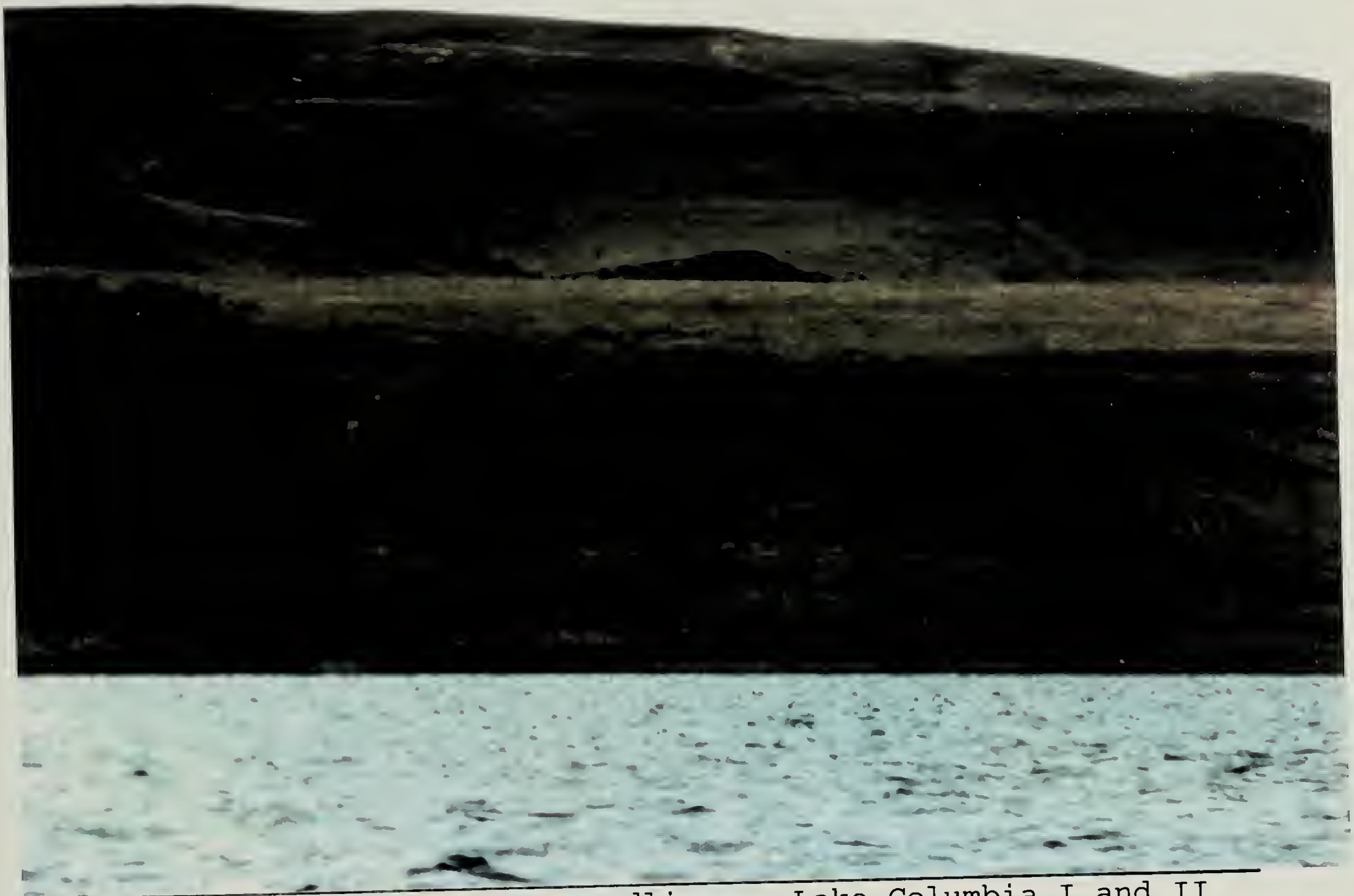


Figure 6 - Neal Canyon strandlines. Lake Columbia I and II Lake levels in the Grand Coulee Quadrangle, 4/5/85

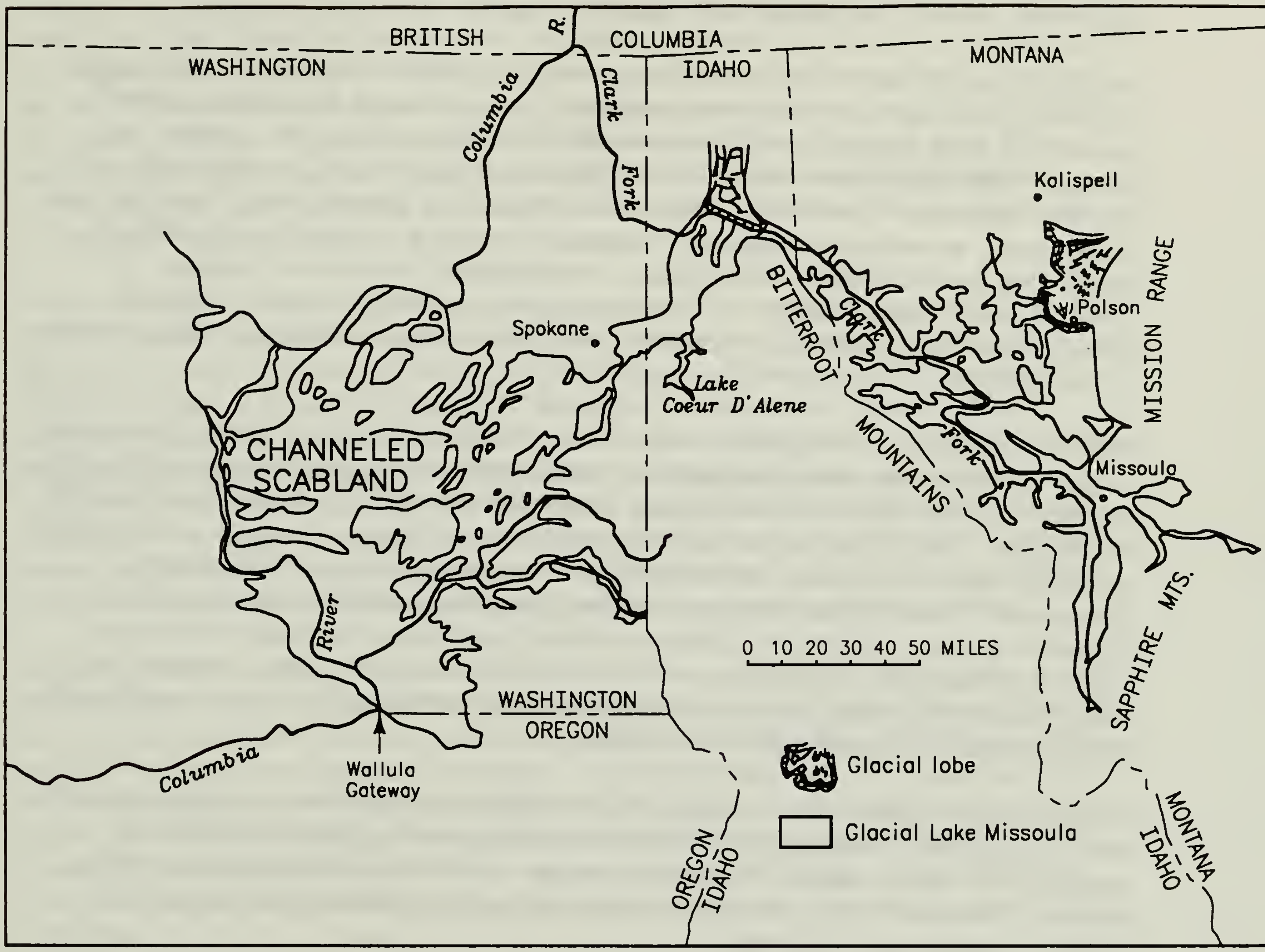


Figure 7 — Map showing relation of Lake Missoula to Channeled Scablands.

Waterfall retreat stripped the basalt cover from the underlying resistant granitic rock. Subsequent erosion by the diverted Columbia River and especially the numerous outburst floods (jokulhlaups) from glaicial Lake Missoula created progressively lower elevation spillways fro glacial Lake Columbia through the Grand Coulee. These lower base levles in turn helped create various levels of terrace development. Erosion of the bedrock lip terminated at the present 1530-foot (466 m) elevation when large catastrophic floods from glacial Lake Missoula stopped.

Strandlines record lake levels and terraces record lake bottom elevations. The stepped terraces suggest that lake history was punctuated by episodes of downcutting. Flood erosion in a deep lake is an unlikely cause and is not supported by the presence of abundant high energy flood sediments and flood landforms in the Lake Roosevelt area. However, evidence of late floods downstream from Grand Coulee in the Wenatchee and Chelan areas, as well as the apparent trenching or notching of lake bottom sediments, suggest that Lake Columbia itself became a self-dumping lake as the Okanogan or Chelan glaciers became smaller. When these glaciers retreated from the Columbia Valley, debris dams continued to impound water as recently as the Glacier Peak eruption 11,200 years ago.

The 1700-foot (518 m) Nespelem terrace (Lake Columbia II) can be traced downstream to near the Nespelem River and upstream to the Castle Rock area where the kame delta complex near the former ice front grades from 1880-foot (573 m) elevation to the 1680- to 1760-foot (512-537 m) level a few miles downstream. Terrace remnants can be traced up the Spokane River valley past Little Falls to the mouth of the Colville Valley (Chamokane Creek) where outwash from the Springdale moraine merges into the Nespelem terrace. The Mt. St. Helens set S ash found in the Nespelem terrace near Elmer City dates part of this terrace at about 13,000 years B.P. Surface elevation of Lake Columbia II was higher than the kame delta (1880 feet; 573 m) and lower than the Nine Mile lateral moraine (1920 feet; 585 M).

The sediments coarsen where tributary valleys spilled into the Nespelem Lake, especially near the San Poil, Enterprise, and Chamokane Valleys where glaciers supplied an abundance of coarse debris. Most of the terrace in the lower Columbia River valley contains lacustrine, varved sediment which is interbedded with sandy units that are mostly of catastrophic flood origin.

Catastrophic floods continued every few decades (up to 55 varves between flood units) and erosion through the granite lip of Grand Coulee continued until the present level of 1530 feet (466 m) was reached. A major, widespread terrace at the Lake Columbia III level, (1560 feet; 476 m) can be traced to near Marcus in the Columbia River valley and through the Turtle Lake quadrangle along the Spokane Valley to Long Lake Dam, about 35 miles (56 km) upstream from the Columbia River.

Flood sediments are of increasing importance up the Spokane River Valley and flood bars often mask the underlying sediments and their elevations. The lacustrine terrace sediments continue into the upper Grand Coulee where they end near Steamboat Rock. Their elevation here ranges from at least 1580 feet (482 m) to 1640 feet (500 m) and may, in part, be related to a higher bedrock base level or a possible moraine southwest of Steamboat Rock reported by Bretz (1932) that was subsequently reworked into a pendant bar. Later floods and the diversion of the Columbia River into Grand Coulee breached the lacustrine fill but was not severe enough to completely erode the sediments away. The Lake Columbia III level was abandoned when the Columbia River resumed its preglacial course along the Columbia River valley below the Grand Coulee Dam site. An ice or debris dam still persisted in the Columbia River valley as the 1400-foot (427 M) Lake Columbia IV terrace can be traced downstream to the Omak Trench (Kiver and Stradling 1982). Shallow remanents of Lake Columbia IV persisted at least to 11,250 years ago when ash from the Glacier Peak volcano was deposited into lake beds in the Lake Roosevelt area.

Whereas isostatic effects on the Lake Columbia I and II terraces can be expected to be minimal because they are located at and beyond the southern edge of the ice margin, segments of Lake Columbia III and IV terraces extend northward up the Columbia Valley into areas occupied by substantial thicknesses of ice where isostatic rebound might be expected to play a more substantial role. The rapid advance and retreat of late Wisconsin ice allowed perhaps only 2000 years of maximum thickness and loading to occur which was probably not enough to produce a significant long-term isostatic uplift with appreciable terrace deformation. Thus, much of the isostatic adjustments occurred before the sediments accumulating in the glacial lake reached the lake surface. Perhaps only about 40 feet (15 m) of terrace deformation due to isostatic effects occurred.

Following Lake Columbia III, base level reduction was accomplished by changing ice or debris barriers in the Columbia River downstream from Grand Coulee Dam. Again the Columbia River notched into the older lake sediments and deposited the 1400- to 1480-foot (427-439 m) Lake Columbia IV terrace. It is widespread from the Canadian border to the Omak Trench downvalley from Grand Coulee Dam where it may have discharged around an ice or debris dam and onto the simultaneously forming Great Terrace of the Columbia (Kiver and Stradling 1982). It also extends up the Spokane River valley and through the Little Falls quadrangle where it terminates beneath the waters behind Long Lake Dam.

The last recognizable terrace level above the reservoir is at 1320- to 1360-foot (402-415 m) elevation and consists of outwash and alluvium over lacustrine sediments in the upper Columbia River valley and alluvium and flood gravels and sands interbedded with lacustrine deposits in the lower Columbia River valley. At least some of the sediments in this terrace were inset (backfilled) after the valley had been partly eroded out. Those sediments that were backfilled are some of the youngest Pleistocene sediments exposed along the reservoir.

GEOLOGIC CONSIDERATIONS

Landslide Studies

Introduction

Landslides are a part of most landscapes and the Columbia River valley is certainly no exception. Although no historical summary is available, it is apparent that some landslide activity existed prior to the filling of Lake Roosevelt and that the area has had a long history of landslides. Flint and Irwin (1939, p. 688) and Jones and others (1961) noted the existence of landslides contemporaneous with the presence of glaciers when climatic conditions were wetter than the present and even deeper lakes occupied the Columbia River drainage system. Steepening of slopes by glacial erosion, removal of ice support with collapse of ice-contact sediments, and fluvial erosion all contributed to the large number of landslides that occurred some 12,500 to 17,000 years ago when ice age conditions last existed here.

Pardee (1918, p. 14) noted that except for the steep slopes and cliffs along the San Poil River valley, most of the area had wide cross-sections and moderate, relatively stable slopes. However, the photograph (Pardee 1918, P1.V) at the mouth of Nez Perce Creek (Hunters 15 minutes quadrangle) showing a large landslide and the existence of Landslide Rapids (Pardee 1918, P1.1) Section T31N, R36E, indicates that some landslide activity existed prior to construction of Grand Coulee Dam. Numerous related landslide scars mapped during the airphoto and field study record slope failures a few hundred to a few thousand years old.

By flooding the valley and adding water to the surrounding slopes, man is partially returning the area to the wetter conditions of the past and has greatly speeded up some of the natural processes. The increased construction of houses and other buildings will only aggravate these conditions and place more people and property at risk.

Although one of the main objectives of this study was to broaden the understanding of the geologic events to affect the Lake Roosevelt area by studying and mapping the geologic materials in the area, the ultimate applications of the base information accumulated will be in understanding, recognizing, and dealing with slope stability and other problems. Documentation of the nature of geologic materials, location of active landslides, and other information will have value in developing long-range land use plans and possibly for future litigation proceedings. The accumulated data and other information may be useful to verify that certain hazardous events were or were not reservoir induced and that the Bureau of Reclamation has acted responsibly in assessing and dealing with hazards along the reservoir.

The breadth, goals, and nature of this report prevented an in-depth study of landslides and slope processes. The field work and maps fit between a reconnaissance and intermediate detail inventory as defined in U.S. Geological Survey Circular 880 (1982). A detailed study of landslides is being performed by the Grand Coulee Project Office, geologic staff. Recommendations for future studies are included in the chapter on recommendations.

Objectives achieved during this study concerning slope processes and identification of unstable areas include:

1. Mapping of slide materials.

2. Distinguish materials of landslides originating in bedrock from those originating in sediment.

3. Identify features and factors of particular significance to landslides in the Lake Roosevelt area.
4. Develop a broad understanding of slope evolution to assist prediction of location and time of future slope failures.

5. Identify specific areas where more study could be beneficial.

The ultimate goal of this and other studies relating to geologic hazards will be to assist decision makers who will determine how land should be used or not used along the reservoir.

Terrace and Slope Classification

Introduction

Portrayal of slope stability of a large area requires the use of a map format so that spatial relations can be more readily grasped (USGS Circular 880). For very rapid assessments, a color or pattern designation keyed to different degrees of hazard or stability is desirable for both nontechnical and technical personnel alike. Further analysis by technical personnel could involve a detailed level summary that delineates important information about physical conditions near a particular site, land ownership, and other factors.

A continuation of site analysis might involve breaking an area into smaller geomorphic units such as continuous terrace units that share a definite set of physical and groundwater conditions. These terrace units could be given formal names and numbers. Each unit should have a file available that could include photostratigraphy analysis of specific sites, historical summary of slide activity, potentially important geologic conditions influencing the terrace unit, ownership, water wells, observation wells, and other information. By having such information on file, present technical personnel could add important facts, information, and observations to the file and a continuity of knowledge and experience would be assured.

Developed for this report was a map-based, intermediate level of terrace and slope classification that delineates certain factual information about specific sites along the reservoir using a standardized alphanumerical system. The system can be simplified or enlarged to identify as many important conditions and factors as necessary or possible. This classification system recognizes all the important factors affecting slope stability in the Lake Roosevelt areas.

Classification Components

The alphanumeric classification system utilizes eight numerical symbols with letter subscripts. These are printed on a set of quadrangle maps that are furnished as a package separate from this report. The designations were done in the field where conflicts of material composition and other factors could be quickly resolved. The factors are placed in approximate order of importance to slope stability, although conditions can vary locally and what are usually lesser factors might dominate the behavior of a particular slope. The classification components are summarized in Table 3 which follows.

Some of the factors and informational items included in the classification scheme such as the characteristics of the material (especially clay material), groundwater conditions, and terrace height were recognized by Jones and others (1961). Other items, including active landslide activity, armoring of terrace base, farming activities, housing and buildings, and type of landslide are also useful to recognize.

TABLE 3

Landslide Hazards–Alphanumerical Terrace Classification

First Symbol: Landslide activity (number following indicates height in feet of landslide scarp).

- 1 - Abundunt recent or active slides - very little or no vegetation on slide scar or scars (post-dam), over 50 percent of terrace length considered displays slides, may be some older slides present.
- 1a- Some recent or active slides, less than 50 percent of terrace length displays slides, may be some older slides present.
- 2 - Old or ancient landslides present (pre-dam), may be a few recent, minor slides.
- 3 - No evidence of landslides.

Second Symbol: Clay content.

- 1 - Lacustrine silt and clay, horizontal or nearly so, often contains sand or gravel lenses or beds and usually has sand or gravel cap; impermeable material below cap is 5-40 percent of total section.
- 1a- Similar to category 1 except some material in a disturbed, distorted, or convoluted condition due to recent or ancient landslides.
- 1b- Similar to category 1a except contortion due to load or ice override.
- 2 - Negligible clay content. Material that encourages groundwater movement. Mostly sand and gravel, free draining, impermeable material less than 5 percent of total section.

Third Symbol: Groundwater conditions.

- 1 - Abundant groundwater - presence of springs, seeps, hygrophytes, or ponds.
- 2 - Low groundwater conditions - absence of springs, seeps, hygrophytes, or ponds.

Fourth Symbol: Terrace height

- 1 - 100 feet or more - includes 1400',1560',1700',and other high terraces abutting reservoir.
- 2 - 50-99 feet - includes 1360' terrace.
- 3 - Less than 50 feet - includes 1320' and lower surfaces.

Fifth Symbol: Armoring of terrace base.

- 1 - No or minimal armouring.
- 2a- Armored withd driftwood.
- 2b- Armored with rocks.
- 2c- Armored with downed trees.
- 2d- Man-made armor.

Sixth Symbol: Agricultural use.

- 1 - High irrigation (orchard, alfalfa, lawns).
- 2 - Some irrigation (grain crops).
- 3 - No irrigation.

Seventh Symbol: Housing and buildings.

- 1 - High density, gretater than two occupied houses or campground.
- 2 - Medium density, two occupied houses.
- 3 - Low density, one occupied house or building.
- 4 - No occupied houses or buildings.

Eighth Symbol: Type of landslide.

- 1 - Slump flow.
- 1a- Multiple alcove.
- 2 - Slump-flow or slide limited by bedrock.
- 3 - Landslides in artificial slopes (may include natural materials).
- 4 - Bedrock landslide.
- 5 - Skin slides or flows.
- 6 - Talus.
- 7 - No slides.

Types of Landslides

The commonly used method of classifying landslides is to use a two-word description based on the nature of the material involved (rock, debris, soil, or mud) and the type of movement (topple, slide, flow, creep). Working in the Lake Roosevelt area, Jones and others (1961) developed a modified classification that inconsistently mixes, but effectively uses type of movement, material, and geomorphic peculiarities of the landslide. The four categories recognized include:

1. slump-earthflow landslides,
2. multiple-alcove landslides,
3. slip-off slope landslides, and
4. mudflows

Jones et al (1961) felt that an informal classification especially adopted to the lake Roosevelt area is highly desirable to expedite communication between geologists and others working in the area. Such a classification is not "pure" in its theoretical basis but can provide valuable distinctions when dealing on an informal basis at Lake Roosevelt. The modified classification used for this report utilizes elements of the "Jones classification" as well as other geologic and geomorphic factors and includes the following categories:

1. Slump-flow landslides. A similar landslide category was used by Jones and others (1961). The landslides are usually medium to large volume (greater than 7500 cubic yards) involving a rotational slip near the head of the slide producing a concave upward fracture plane and flowage near the lower end or toe of the slide (Figure 8). The landslides can also be called "high terrace landslides" when they occur from surfaces of at least 1400 feet (430 m) or more elevation immediately next to the reservoir. Although some "low terrace" slump-flow landslides do occur, they usually involve less than 7500 cubic yards of material. The low terrace category also includes low elevation sloping surfaces such as those found on alluvial fans immediately next to the reservoir.

2. Multiple-alcove landslides. This category was first recognized by Jones and others (1961) to describe a special type of high terrace landslide. The distinctive characteristics of these landslides is that they produce two or more re-entrants or alcoves that extend headward into the surface behind.

They are a variety of the slump-flow landslide type. The landslide debris often exits through a relatively narrow valley near its lower end. If only the vegetation-covered scars were examined, it might be concluded that there were many landslides over a period of many years. However, Jones and others (1961, p. 16-18) report an eyewitness account where a large multiple alcove landslide formed within a few minutes and enlarged substantially over a period of 12 days in April 1951. Large amounts of groundwater are involved in these types of landslides and although there are only a few examples in the reservoir area, they seem to be associated with high terraces where bedrock channels are buried by Pleistocene age sediments.

3. Skin slides. This type was called slip-off slope landslide by Jones and others (1961) and involves mostly a sliding or flowing type of motion (Figure 9). The incorrect association of slip-off slope landslides with the slip-off slope environment on the inside bend of a stream makes the use of a different term such as skin slide more desirable. Where medium- to course-size material is abundant in low terrace conditions (less than 1400-foot elevation) small amounts of sediment frequently fall or flow over the slope. Removal of sand by deflation or wave action at the base of the slope produces a slow but persistent retreat of the terrace slope. Although not usually subject to catastrophic slope movements, this type of slope process is a substantial threat to development of the many low terraces. Of particular interest are the skin slides occurring in the Seven Bays area where extensive development, including condominiums, golf course, etc., are being planned (Figure 10). Skin slides are only second in frequency to slump-flow landslides.

4. Unconformity landslides. This type of landslide was recognized by Jones and others (1961, p. 39) as a variation of their four main groups of landslides and was called "landslides off bedrock". The plane of failure in this type of slide is the discontinuity surface between sediment and the underlying bedrock (Figures 11 and 12). Either a slumpflow

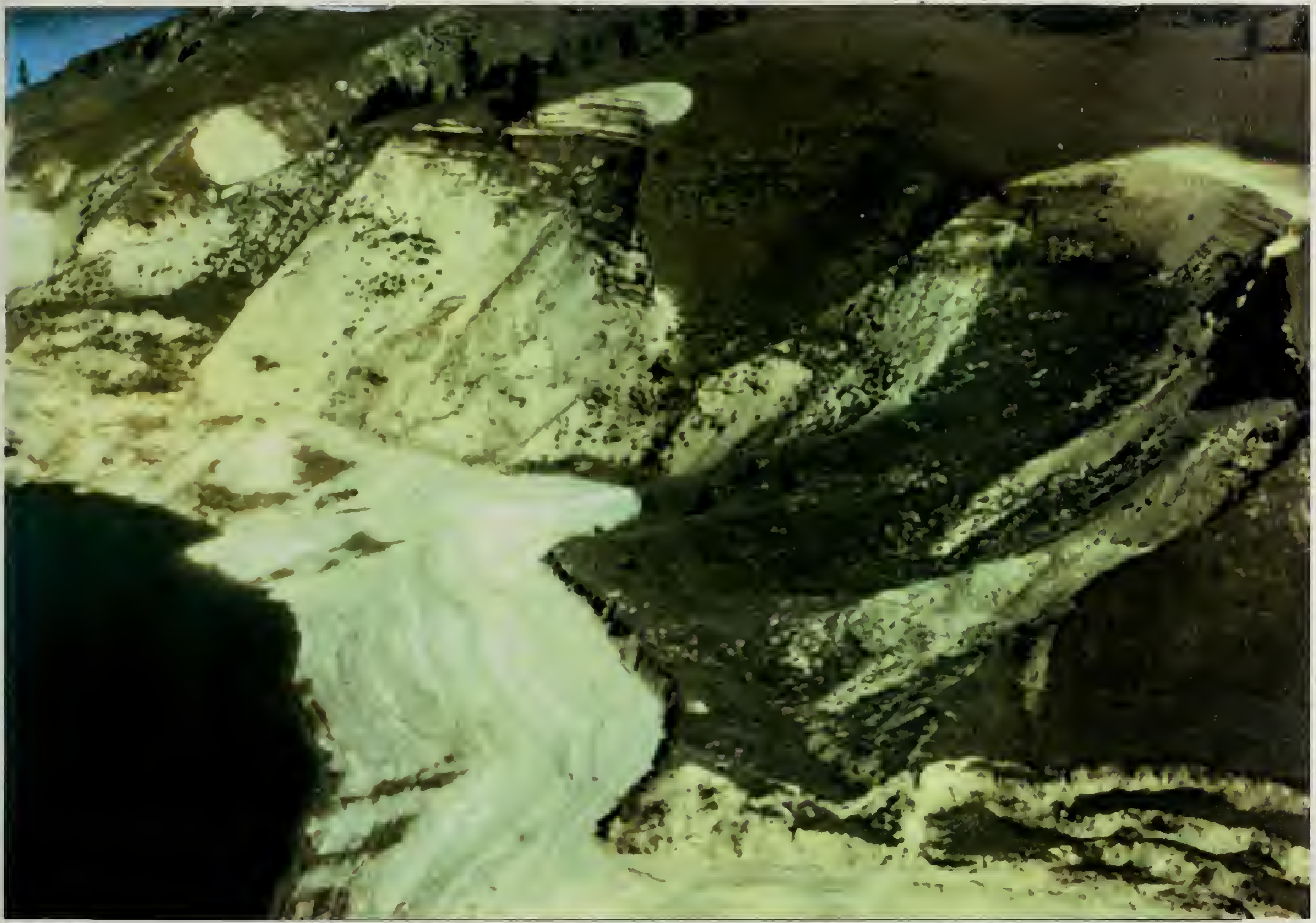


Figure 8 - Slump-flow landslides in Hawk Creek. High Terrace landslides in rhythmically-bedded, lacustrine-flood sediments. Note recent slope movement in lower right. Photo taken on 5/11/83.

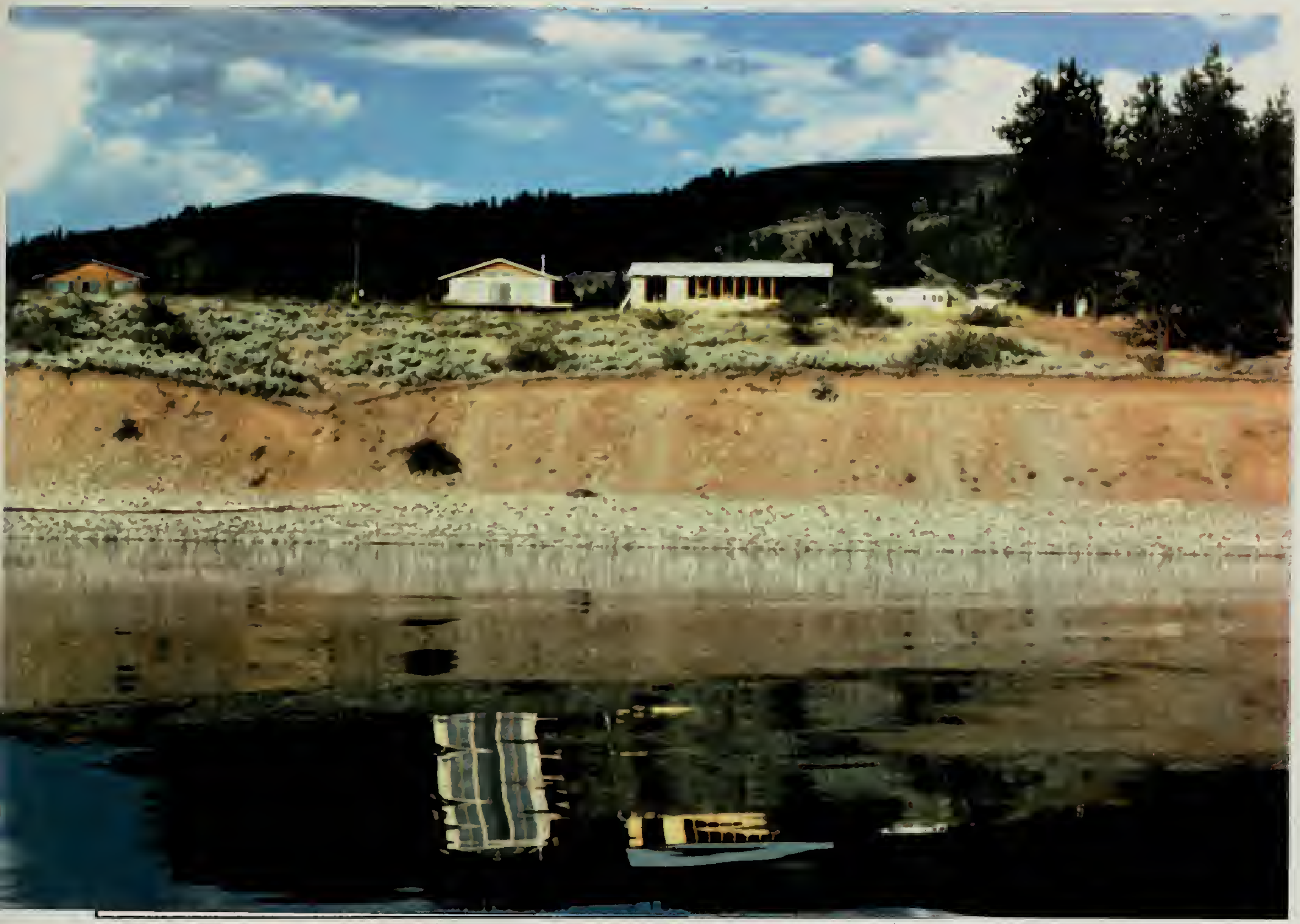


Figure 9 - Skin slides at Seven Bays. Persistent but slow unravelling of debris causes continual slope retreat. Note gravel armor at slope base. Photo taken on 6/14/84.

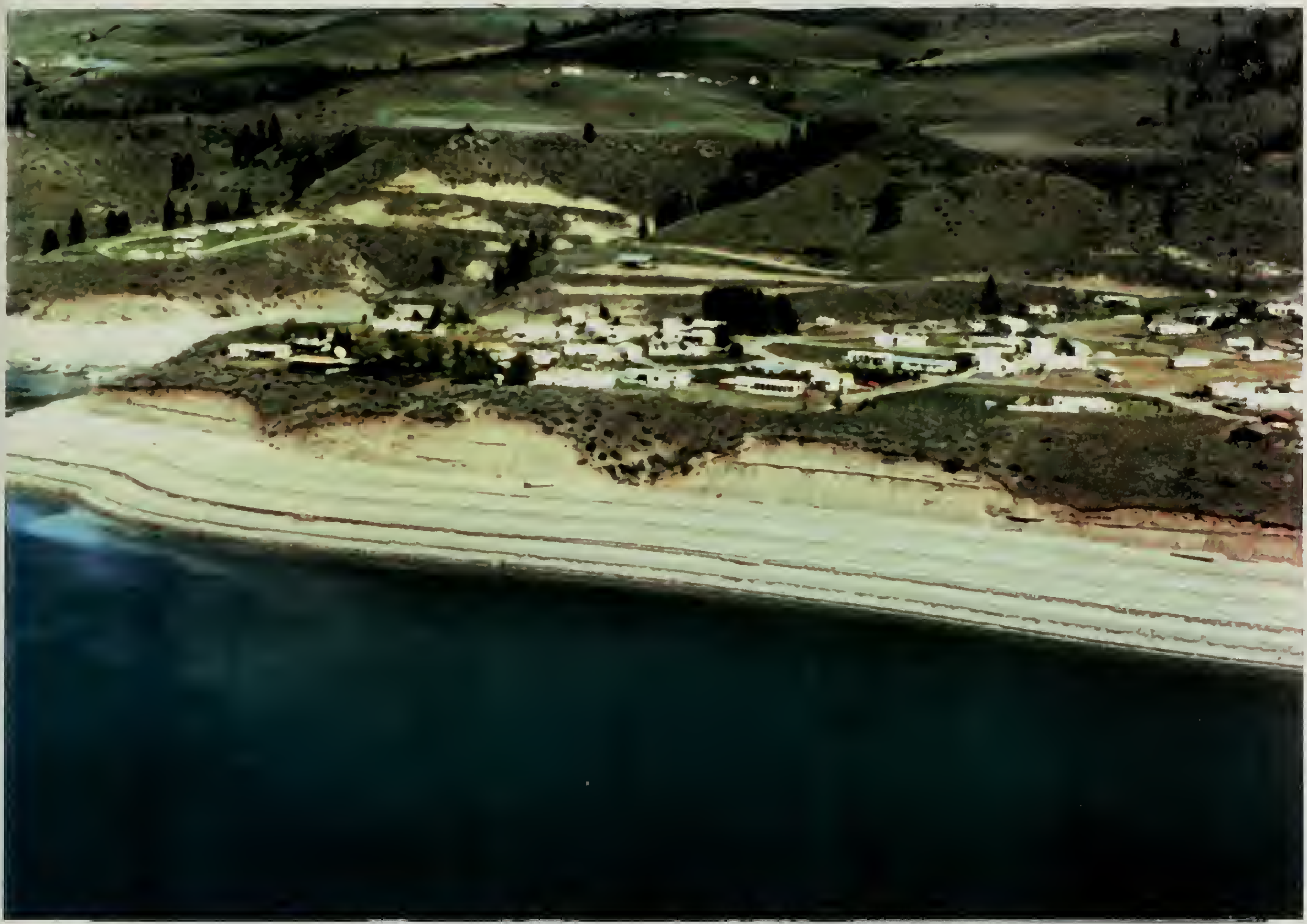


Figure 10 - Airview of Seven Bays development. Photo taken on 5/24/84.

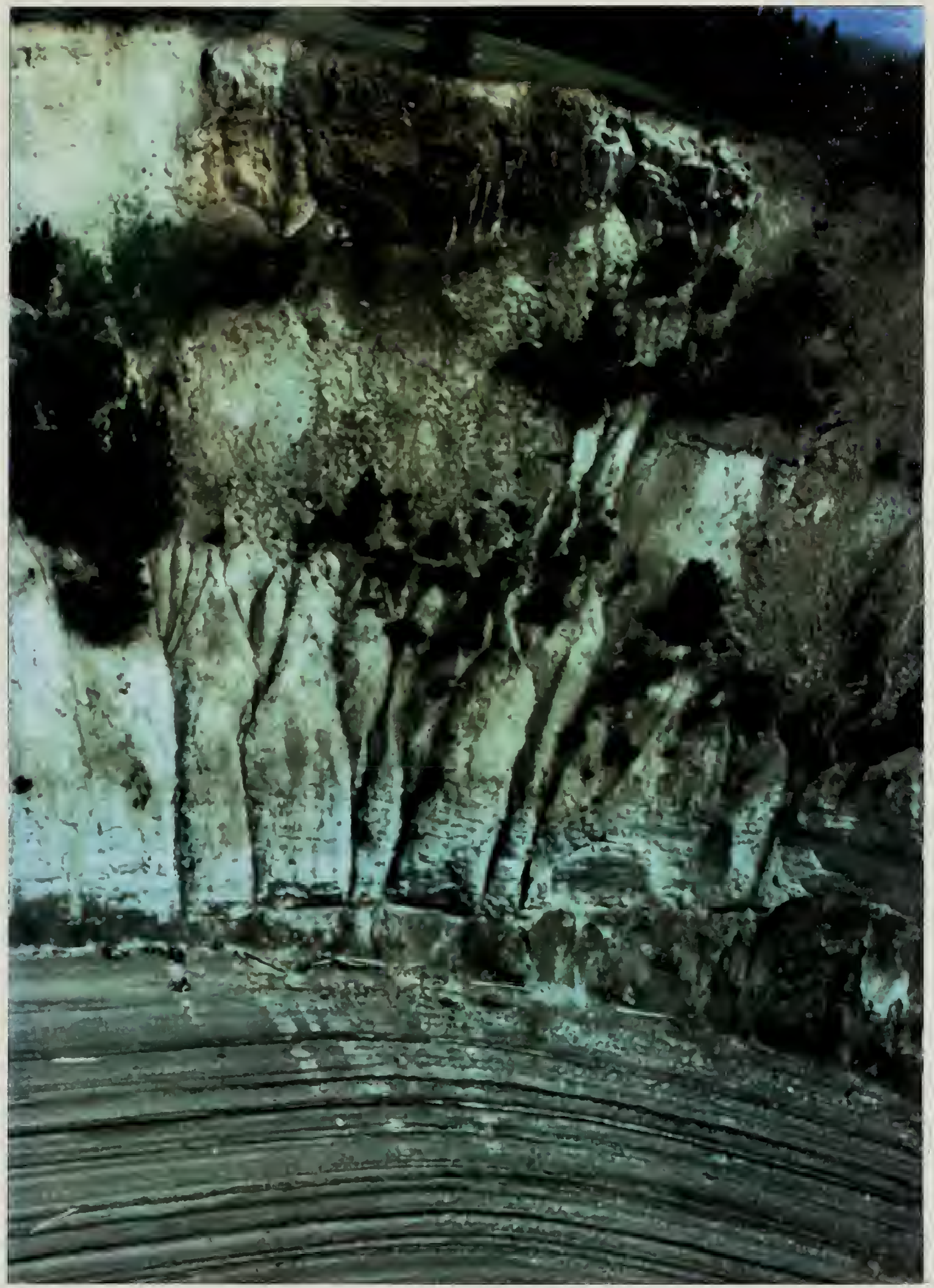


Figure 11 - Unconformity slide in Nez Perce Creek area. Note the Sanpoil Volcanic rock exposed in the crown of the landslide. Photo taken on 5/4/84.

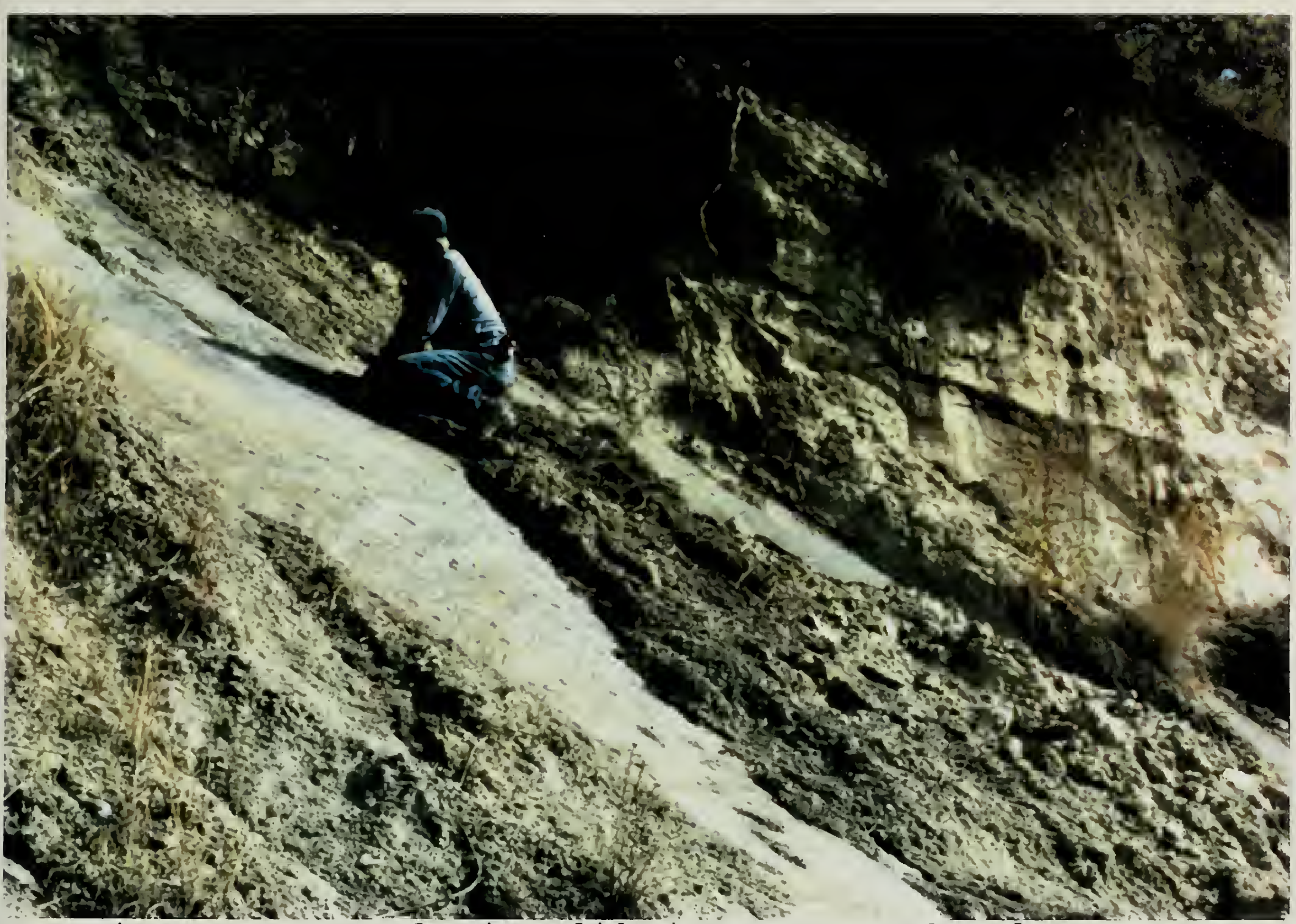


Figure 12 - Unconformity slide in Hunters quadrangle. Glacially-polished volcanic rock provides poor adhesion with lacustrine mud. Photo taken on 8/31/83.

or sliding type of movement occurs.

This type of landslide is of interest for a number of reasons. It represents the final stage in the sequence of sediment removal begun when the continuous cover of sediment deposited in Glacial Lake Columbia was first dissected as base level began to fall (see section on slope evolution). The rate of cleaning off of the final sediment layer is dependent on a number of factors including the volume of the sediment and rate of removal of debris by waves and currents operating at the slope base.

Monitoring of some of these unconformity slides to determine rates of slope retreat should be relatively easy because of the permanency of the bedrock marker. Particularly good areas to accomplish this would be at the mouth of Hawk Creek (NW ¼SW ¼ Section 23, T27N, R35E, Lincoln SE quadrangle) and near Nez Perce Creek (SE ¼ Section 34, T31N, R36E, Hunters 15 minute quadrangle).

Complete cleaning out of sediment removes the hazards associated with unconsolidated material and the controlling influence on slopes will then be the bedrock behind. Where bedrock is exposed, the desire to develop the land is low even though the stability of the slopes is high, unless there are structural defects such as gouge zones or highly fractured rock. In some cases, such as at Hawk Creek and nearby areas where basalt underlies the unconformity, exposure of basalt could increase the probability of large magnitude basalt landslides by removing the buttressing effect of terrace material, increasing the shear stress at the base of the slope, and exposing rock that may have severe flaws that effect its shear strength.

The nature of the sediment-bedrock unconformity surface and lithology of the bedrock may influence the stability of an unconformity landslide. Buried granite surfaces that have experienced exfoliation have relatively smooth, rounded surfaces that encourage sediment movement on top of the bedrock. Glacially polished rock surfaces are more common in the upper Columbia River valley and present very low friction surfaces for sediment to cling to. Limestones are particularly susceptible to glacial polish and are very common near Kettle Falls and areas to the north.

5. Bedrock landslides - non basalt. Bedrock slopes along Lake Roosevelt are relatively stable and have experienced mostly small rock slides. The avoidance, so far, of bedrock areas by developers

and individuals has also served to minimize potential hazards. The bedrock units in the Lake Roosevelt area are relatively competent and generally hold steep, high slopes with very few slope failures.

Landslides are more likely to occur in areas where steep or oversteepened slopes exist. Glacier activity in the upper Columbia River valley (above the Columbia-Spokane River confluence) was particularly effective in steepening slopes. Bedrock slides can result from lateral and vertical cutting by streams, undercutting of valley walls by catastrophic-flood currents, and human disturbances including road and railroad construction.

The degree of fracturing and fracture orientations also influence the ability of rock to withstand the shear forces generated on a given slope. Notable changes in rock characteristics often coincide with known or suspected faults. These zones are often recognizable on airphotos and topographic maps as lineaments. Rock cliffs or valleys along these lineaments that extend down to the reservoir should be considered prone to landslides until proven otherwise.

The only important bedrock landslides occurring during this 1983 to 1985 study was one that occurred in 1983 in the NW ¼ Section 25, T34N, R36E (Inchelium 15 minute quadrangle) along the main north-south highway on the right bank (Figure 13). Here an undercutting for the roadway produced a nearly vertical rock wall and vertical fractures in Ordovician dolomite encouraged slope failure.

The largest recognized nonbasalt landslide in the Lake Roosevelt area occurs at Whitestone Rock in the Wilbur (15 minute) quadrangle. Whitestone Rock is a granite dome of probable early Tertiary age intruded along the Brody Creek-Jump Canyon lineament. The east face rises nearly vertically 750 feet above maximum reservoir elevation. Vertical fractures parallel to the east face may have been generated by movements along the lineament. Lake Missoula floods, fluviatile erosion, and rockfalls and rockslides have removed the east side of the dome and exfoliation parallel to the exposed face helps maintain the spectacular cliff.

The cause of bedrock landslides is likely complex with a combination of circumstances and conditions leading to slope

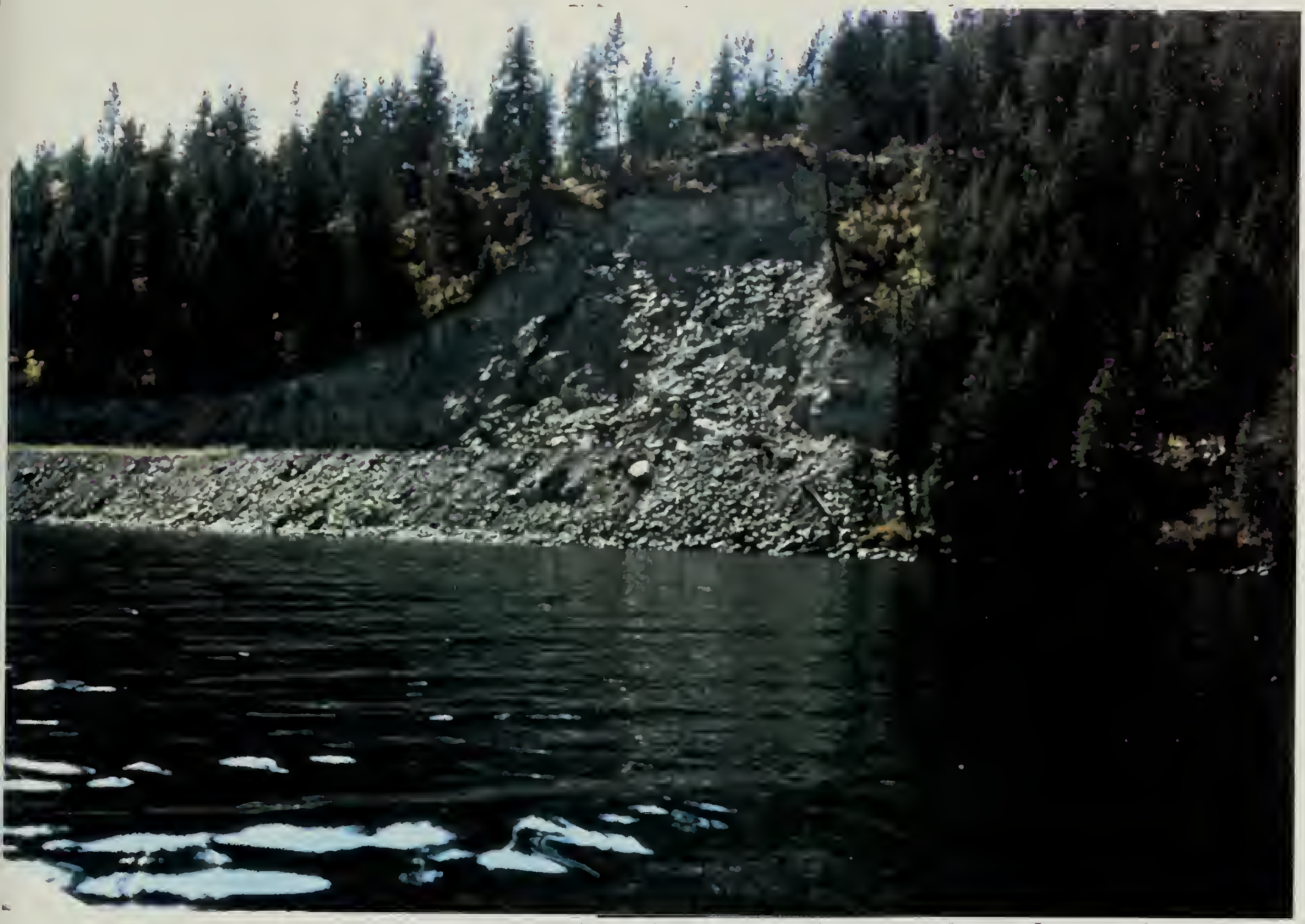


Figure 13 - Bedrock landslide in Inchelium quadrangle. Photo taken on 9/7/83.

failure. Most of these bedrock landslides are unrelated to the present reservoir processes unless erosion of terrace material by wave activity and landslide acts to remove support from the rock base and permit increased shear stress on slopes.

6. Bedrock landslides - basalt. The geographic location of the Columbia River on the edge of the Columbia Intermontane Province was controlled by extensive flows of mostly Miocene age basalt. The lava filled former river channels and pushed drainages towards the edge of the province where many occur today. Basalts extending north of the Columbia and Spokane Rivers are usually quite thin and located where topographically low areas permitted more northerly extensions of lava to occur. Such areas occur downstream of Grand Coulee Dam in the Omak trench and upstream of Lake Roosevelt in the lower end of the Colville-Chanokame Valley and Little Spokane River.

No significant northern extensions of the lava fields occur in the Lake Roosevelt area. The topographically low area now occupied by the San Poil River valley is a more recent development which resulted from breaching of a drainage divide near the Devils Elbow along the San Poil River by Pleistocene glaciers (Pardee 1918, p. 45). No Columbia River basalt occurs north of the few small outcrops located 4 miles north of the Columbia-Spokane confluence. Perhaps the upper Columbia River valley, or at least the segment from Ft. Spokane to Miller Mountain, was not present during Miocene time. A likely location for the main channel during Miocene time for northeastern Washington is the Colville Valley.

Many large landslides in eastern Washington occur where cliffs of basalt are exposed. Numerous examples occur in the Spokane area, Little Spokane River basin, lower end of the Colville-Chamokane Valley, and many other sites including the lower Columbia River valley portion of Lake Roosevelt. Typically, slope failure involves a slump-flow type of movement. Many of these landslides are post-glacial in age and formed under the wetter climatic conditions that existed between 7000 to 11,000 years ago (Mehringer 1985). Present conditions appear too dry to cause similar large landslides or to reactivate older ones.

Most of the basalt landslides have a subdued but recognizable morphology (Figure 14). One exception, however, is the large, very fresh landslide on the east end of the town of Grand Coulee (NE ¼ Section 13, T28N, R30E). The scar is quite distinct here, hummocky

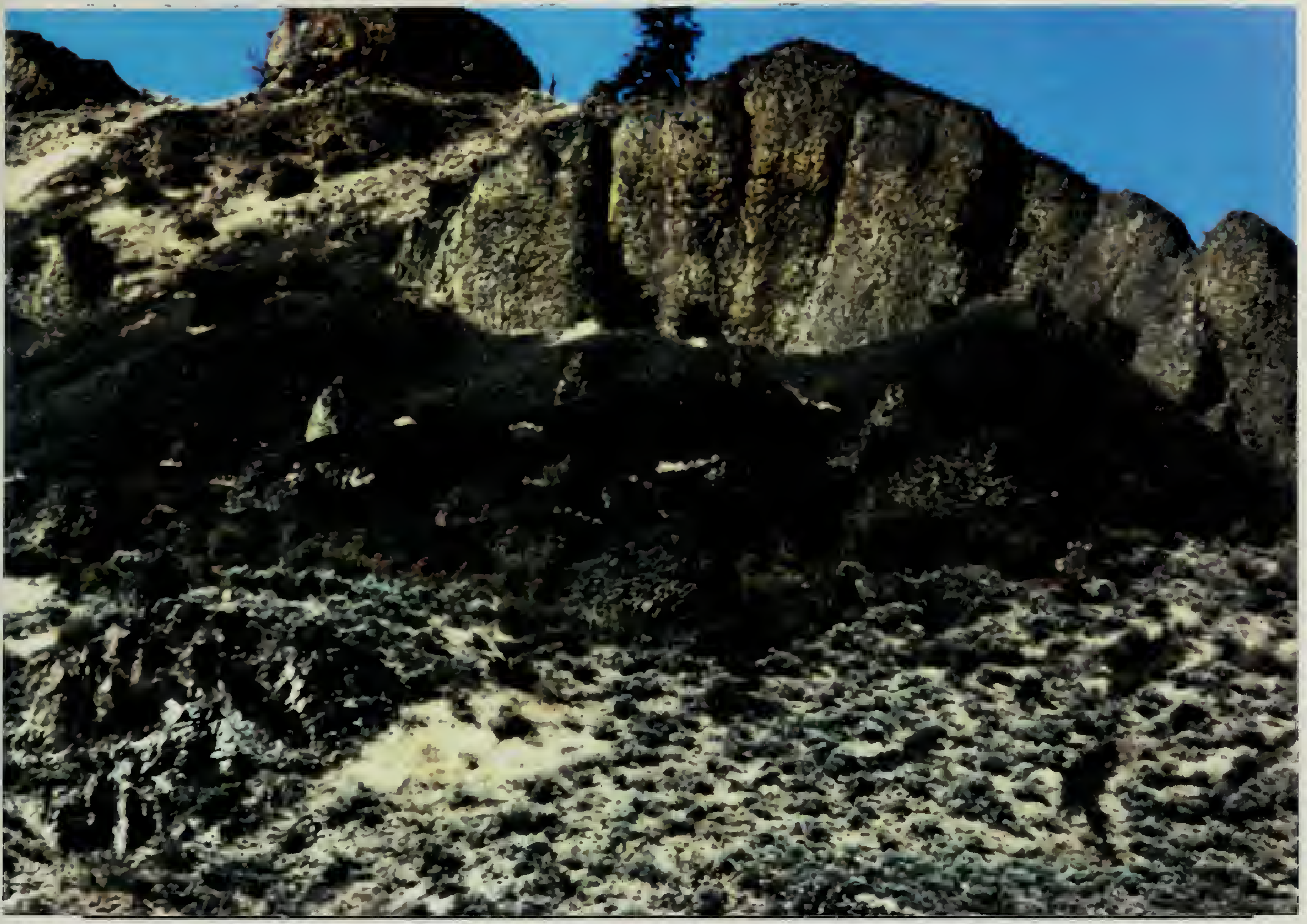


Figure 14 - Basalt landslide in Hells Canyon area (Sec. 35, T29N R.31E.). Photo taken on 9/28/83.

topography is distinct and very little recent windblown or slope-washed sediment occurs in the large closed depression at the head. Lichen-free slide debris at the toe suggests that recent, perhaps historic, movement occurred here.

The physical characteristics of basalt that often induce slope failures are the existence of horizontal planes of weakness. These can be due to interbeds or extensive zones of pillow basalts. The presence of the fine-grained Latah Formation beneath and interbedded with the basalt is a major cause of instability.

In addition to structural weakness along these horizontal discontinuities, when the clayey components in the Latah and pillow zones become wet, movement is further encouraged and can produce a large rectangular block that rotates downward along a concave upward failure plane.

Fortunately, the basalt in most cases is back away from the edge of the reservoir and the underlying granite is exposed at the reservoir edge. If the basalt were partially submerged, then discontinuities might be further weakened and large reservoir-induced landslides could occur. Where the basalt-granite contact is close to but above reservoir level, such as near the town of Lincoln, groundwater loading due to natural or man-induced causes could trigger a landslide that might appear to be reservoir induced. Identification of the presence of granite outcrops and, therefore, the location of the unconformity is documented by the geologic maps and its specific notation in this report.

Factors Affecting Landslide Development

Introduction

Slope failure occurs when shear stress exceeds the shear strength of materials comprising a slope where shear strength is equal to:

$$S = C + R\tan \varnothing$$

R = normal stress on slip face
C = cohesion
$\varnothing$ = angle of internal friction

When shear stress exceeds shear strength, failure will result. Increases in shear can be from increased weight due to groundwater loading, steeper slope angle, and particularly slope height. Thus, those processes that help clear the base of the slope of debris are of the utmost concern because they tend to maintain the maximum bank height, slope angle, stress, and probability of slope failure.

In combination with the terrace classification as well as making general observations, certain relations and associations of factors and the occurrence and rate of landslide activity were made. As many of these factors as possible were included in the terrace classification. Additional comments on these factors as well as others not included in the terrace classification summary are briefly discussed here.

Material in Terrace

Basic to most slope failures are the unique characteristics of the material and how it behaves under different conditions of loading, stress, and the addition of water. Permeability is a key factor that helps determine whether groundwater conditions will reduce or destroy slope equilibrium. The extensive lacustrine clays and silts derived from the former glacial lakes are involved in most of the landslides occurring along Lake Roosevelt. The number of impermeable layers and their thicknesses vary widely but their effects on landslides has not been fully evaluated.

The textural characteristics of till are highly variable. Permeability tends to be moderate at lower elevations along the reservoir where ice deposited sediments directly into a glacial lake. The degree of working by currents will influence the amount of sorting and increase the permeability of the resulting sediment.

However, where clay-rich, impermeable lodgment till areas exist, landslide hazards can be extensive. Such areas are much more prevalent in the upper Columbia River valley because of the recency of glaciation and the thicker Pleistocene glaciers to the north.

Cementation of Sediments

Soil-forming processes and groundwater action can cause induration of sediment which affects the strength and behavior of materials. Cementation by CaC03 is very common although some siliceous cements are present. Carbonate cement in the upper reservoir is abundant because of the abundant limestone bedrock. Its influence seems to mostly be a case-hardening effect on certain slopes such as the exceptionally high and steep slopes and landslides along the Marcus moraine area (SE ¼ Section 29, T37N, R38E, Marcus 7.5 minute quadrangle). The location of the railroad right-of-way a few hundred yards away from this scarp head could eventually produce a serious property loss if slope retreat continues. It is extremely difficult to penetrate the carbonate armor covering the talus slope here even with a pick ax. The cementation extends 60 to 90 feet up the slope to the base of a thick kame-delta gravel which is also well indurated. Remobilization of some of these materials occurs seasonally as indicated by small scale rivulet levees and other features. An examination of these slopes during the spring might disclose whether these scarps enlarge on a yearly basis or exceptional weather conditions are necessary to permit significant enlargement. Ultimately, the railroad property and nearby farm fields will be affected by this retreating slope.

Cementation in the lower reservoir area is localized and partial in many areas. The drier climate in this area encourages caliche development in the soils but most cementation is associated with water perching along an impermeable clay layer. Cementation can occur in sands and gravels both immediately above and below the impermeable layer although cementation below seems to be most common.

Extensive cementation of gravel and some sand layers above a clay unit in the very large Jackson Springs landslide (Lincoln SE quadrangle) has lithified gravels into a conglomerate that is as much as 15 feet thick and extends 10 feet or more back into the hillslope in some areas (Figure 15). The lithification of such a massive unit increases the strength of a gravel unit which may in turn encourage larger landslides rather than a number of more frequent, smaller landslides. Similar conditions may prevail along the westerly continuation of the Jackson Springs terrace 1560 feet (480 m) and should be investigated in greater detail.

Buried Pleistocene Valleys

The extensive glacially-dammed lakes in the Columbia River valley produced thick accumulations of sediments that randomly buried the lower valley topography. Re-establishment of the surface drainage and downward cutting allowed the Columbia River and its tributaries to sometimes locally acquire courses different from their original ones. Some courses became established across bedrock leaving old, abandoned valleys filled with sediment. These buried valleys can act as conduits for groundwater flow and load or saturate sediments, thereby making slope failure more likely.

Jones and others (1961) recognized this condition in the Nine Mile Creek (Wilmont Creek 15 minute quadrangle) and Sherman Creek (Bangs Mountain 7.5 minute quadrangle) areas. Both areas have severe landslide problems. Sherman Creek is superimposed across a ridge of rock on the north side where it has cut a spectacular, vertical-walled canyon some 400 feet deep.

Another area of possible concern is the Kettle Falls-Mission Bay (Reclamation's official name) area. Housing is being constructed on the 1600-foot (490 m) terrace on the north side of the land jutting out into the reservoir in Section 13, T36N, R37E. Two hypotheses that are consistent so far with available mapping information and the few well logs available is that the old channel of the Columbia may have flowed east of Hawks Nest (Kettle Falls 7.5 minute quadrangle) or the Colville River may have flowed through the area near the town of Kettle Falls and joined the Columbia River in the "Mission Bay" area.

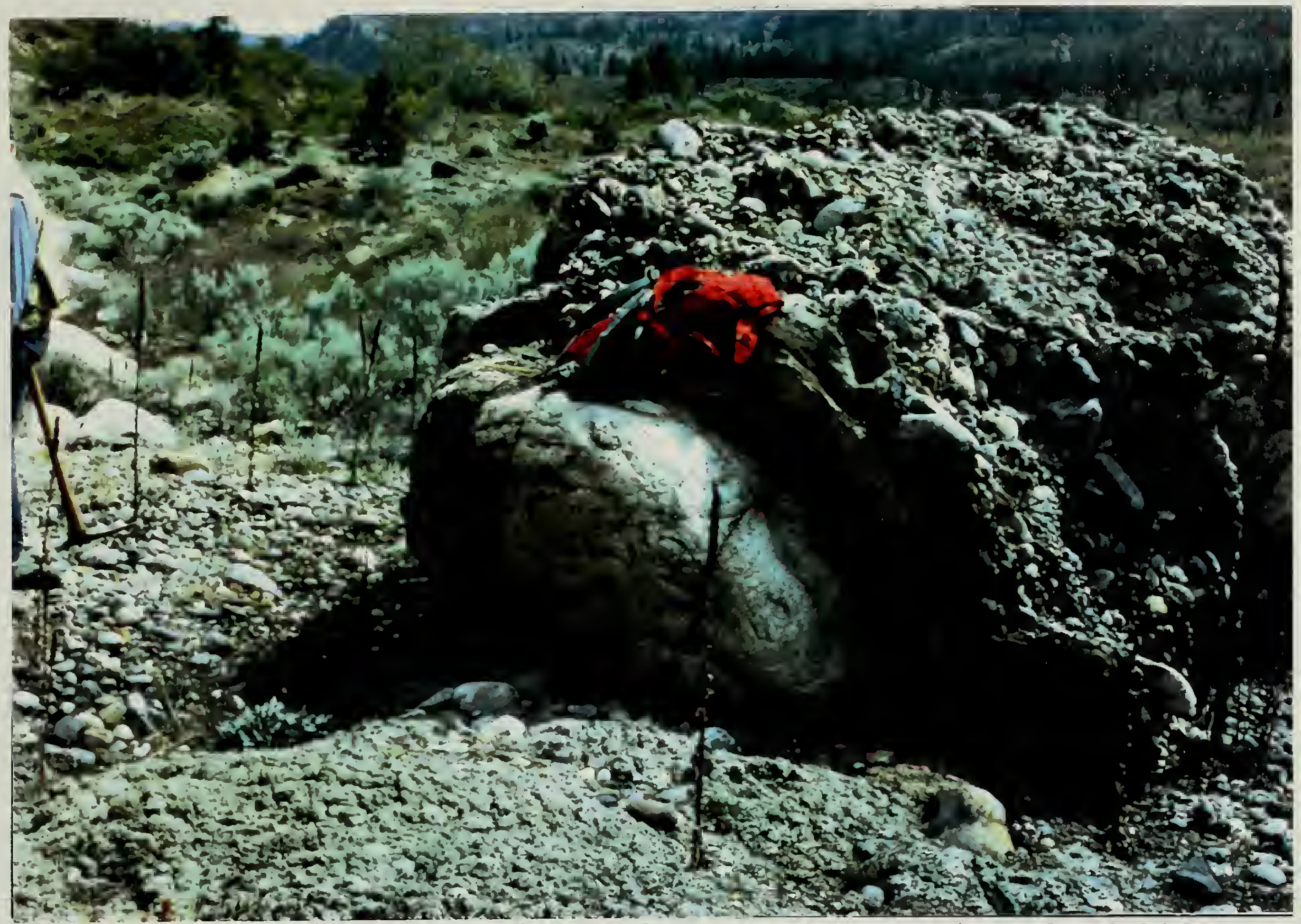


Figure 15 - Calcite-cemented gravels in Jackson Springs landslide. Photo taken on 5/18/84.

Post-glacial downcutting may have superposed the Columbia River onto the rock ridge that forms Kettle Falls (now flooded by the reservoir) and left a former valley buried by lacustrine sediments in the "Mission Bay" area. The combination of a major high terrace and groundwater loading may account for the numerous, large magnitude landslides in the area and could pose a serious hazard to the developed property and the area residents along "Mission Bay".

Other areas where buried channels may occur include Little Falls, China Rapids (near Hawk Creek, Lincoln SW quadrangle), Hellgate Rapids (Wilbur 15 minute quadrangle), Hall Creek (Inchelium 15 minute quadrangle), and the China Bend-Flat Creek valley (China Bend 7.5 minute quadrangle). The Inchelium area is also of great concern because of the large number of people and buildings in the town and the recent landslides along Hall Creek.

Each major tributary valley should be examined closely for evidence of buried topography as well as those areas where rapids existed prior to the filling of Lake Roosevelt. Pardee's (1918 Plate I) map shows the location of these former rapids.

Lineament Traces

A lineament is a nongenetic term that describes a linear or curvilinear alignment of topographic or tonal trends on the earth's surface. Lineaments are most easily recognized using remote sensing techniques including airphoto and map studies. Many such features, but not all, have geologic causes. Geologically-controlled lineaments often produce avenues for groundwater movement and can therefore contribute significantly to slope failure.

Areas where lineaments intersect Lake Roosevelt coincide with a number of highly unstable slope areas and should be looked at in more detail. The position of the Columbia River valley itself is at least partially if not wholly controlled by geologic characteristics or features in the bedrock such as folds and faults. Thus, more detailed lineament studies and their correlation with active slopes would be a useful endeavor to properly identify and understand more about high risk areas.

Terrace Slopes

Terrace slopes were not measured during this study but might be good indicators of stability. A more detailed study specifically dealing with landslides should be done and it should consider slope configuration and angles as potential stability indicators. The toe of the slope and its rate of erosion is also particularly critical to slope behavior.

Sediments deposited directly against ice are characteristically steep and therefore potentially hazardous. If combined with high elevation above the reservoir, such surfaces are especially hazardous. The nine Mile area, already mentioned in conjunction with buried valleys, has ice contact surfaces whose upper elevation is about 1900 feet (500 m), approximately 600 feet above normal pool elevation. The potential for major slides here is high and is borne out by geologic, geomorphic, and historical records of slope failure.

Geologic processes that increase slope angle include running water, waves, glaciers, wind, and man. Although running water was particularly effective during and following the retreat of glacial Lake Columbia, today it still plays a major role where tributary drainages such as Hall, Nez Perce, and Nine Mile Creeks and the Colville River enter the reservoir.

The most stable slopes along the reservoir are nonbasalt bedrock slopes and alluvial fan and debris slope surfaces (Figure 16). In some cases, even these relatively safe surfaces can experience slope retreat but can be stabilized with a minimum amount of shoreline protection (Figure 17). Bedrock slopes, particularly those with steep, high cliffs, are subject to failure but the Whitestone Rock rockfall is the only major one known along the reservoir. Pressure to develop land with a bedrock setting is minimal at the present time but might be an option as further development continues along the reservoir. Alluvial fan surfaces, however, are relatively safe from slope failure but are subject to flash flood and mudflow hazards. In many cases, the fan sediment is deposited onto lacustrine sediment and is subject to more rapid shoreline retreat (Figure 18). Such conditions occur in the Mill Canyon, Bull Pasture (Turtle Lake 15 minute quadrangle), and the Penix Canyon (Wilbur 15 minute quadrangle). Shoreline retreat is slow in these areas but ultimately will endanger some of the dwellings constructed on these and other sites. Interest in developing these types of areas is much greater because of the ease of construction and ready access to the reservoir.

Debris slopes, alluvial fans, and low terraces act as buttresses and protect the higher terrace scarps from erosion by wave action. The presence of these features provides significant protection to many higher slopes and terraces.

Terrace Armor

Terrace armor is the fifth symbol used in the terrace classification and includes materials such as rock, driftwood on the high water beach, downed trees with their roots locked to shore (Figure 19), and manmade constructions. The rate at which landslide debris is removed from the base of a slope determines how soon the scarp will experience another major movement. The time required for a landslide to recur at the same site is a measure of landslide frequency. The nature and amount of debris at the base of the slope as well as the intensity of wave action will influence the landslide frequency. The

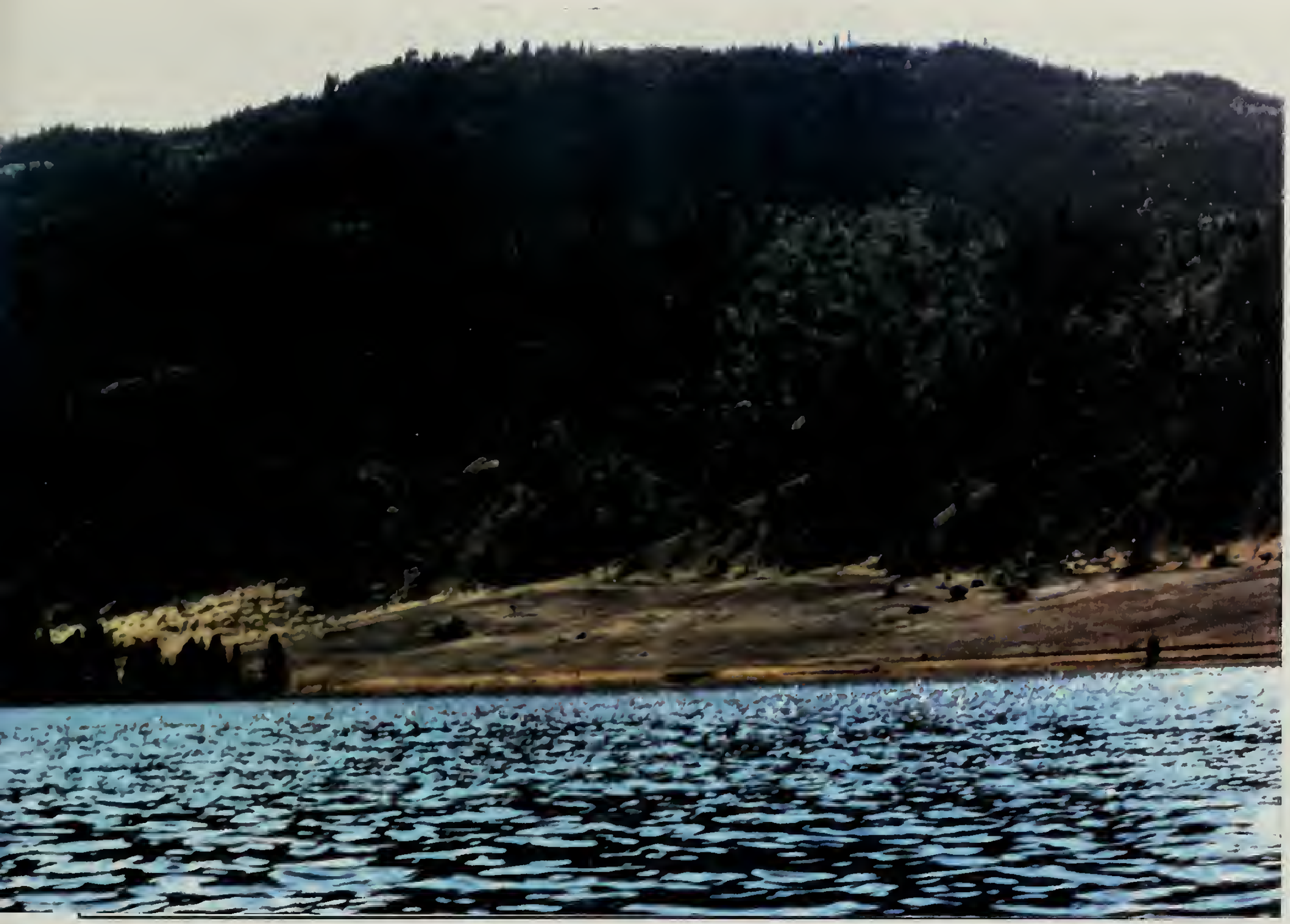


Figure 16 - Relatively stable alluvial slope in Snag Cove area. Gently sloping sediment surfaces in SW¼ Sec. 5 (T.37N., R.38E., Marcus quadrangle). Photo taken 8/6/85.

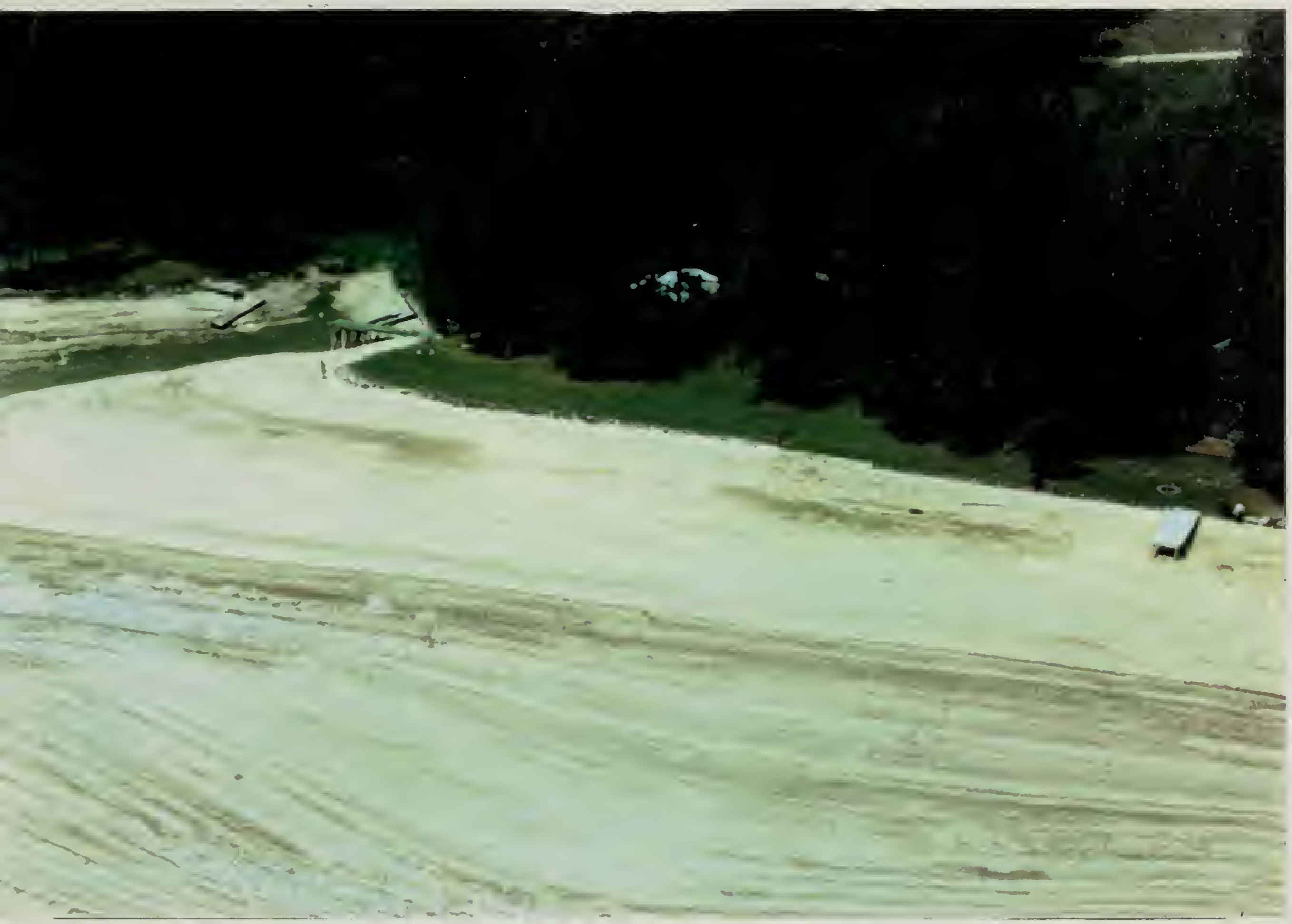


Figure 17 - Alluvial slopes experiencing minor headward retreat. Rip rap, log pilings, and other relatively inexpensive shoreline protection is being effectively used here. Photo taken on 5/25/84.

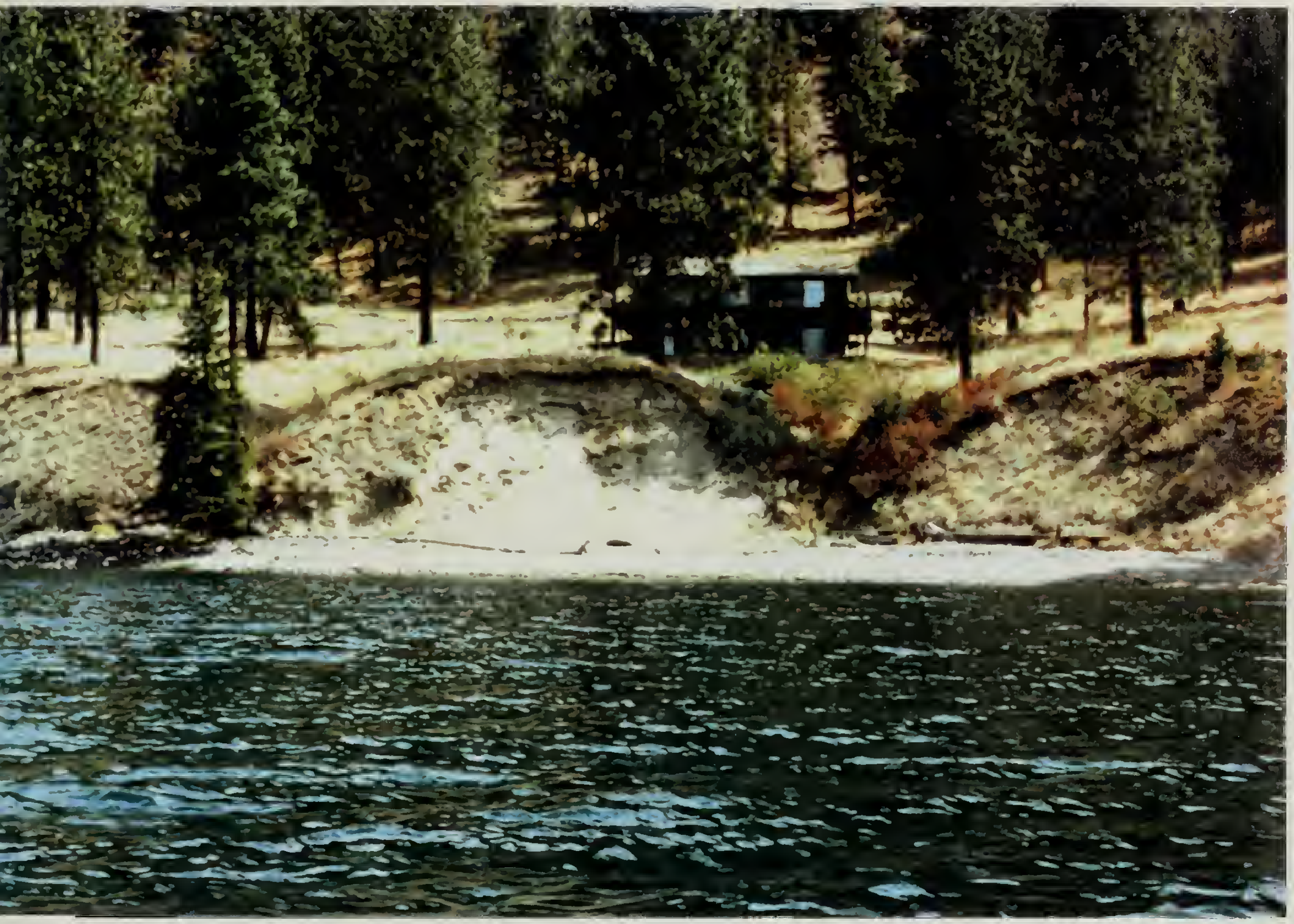


Figure 18 - House in Turtle Lake quadrangle near Bull Pasture. Alluvium over lacustrine mud is actively eroding. Photo taken on 8/21/85.

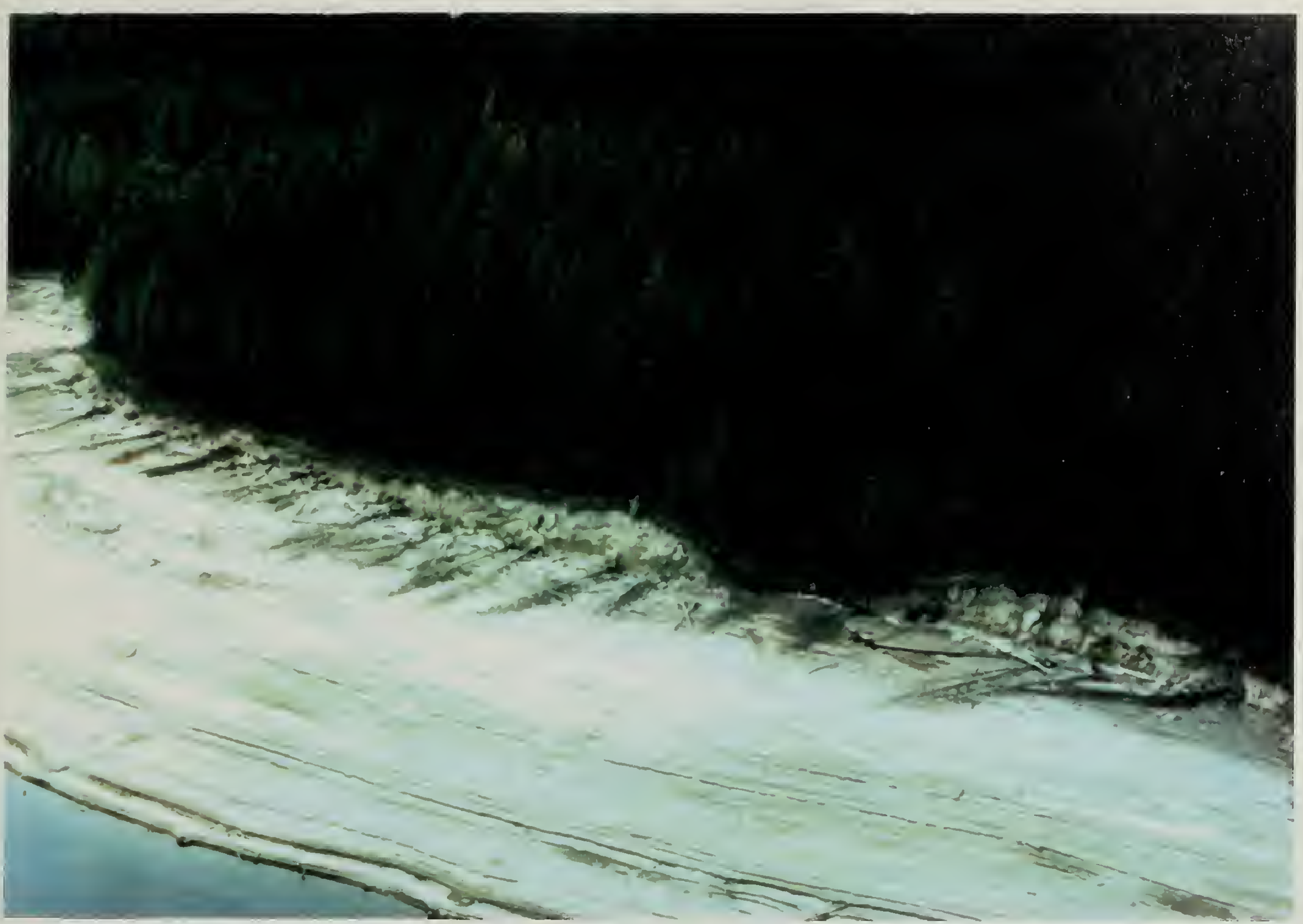


Figure 19 - Tree armor in Inchelium quadrangle (Sec. 30, T.33N., R.37E.). Photo taken on 5/25/84.

types of natural armoring along Lake Roosevelt only slow down but do not stop retreat as would a well-designed riprap or log boom installation.

In areas where gravel lenses occur in the sediments (e.g., SE ¼ Section 14, T27N, R35E; Lincoln SE quadrangle) the shoreline is usually scalloped with small peninsulas or areas projecting into the reservoir where gravels are in the sediments (Figure 20). Gravels armor the peninsulas and slow the rate of slope retreat.

Large driftwood tree trunks act as an armor on some beaches and protect the slope behind except at high water level. Logs then begin to float and act as battering rams increasing the removal of materials. High water levels are particularly effective in debris removal of not only floating debris but rock debris as well. Slope retreat would be retarded significantly if high pool elevation were seldom reached. Much of the work of debris removal at the slope base is accomplished at high lake level.

Observation stations to monitor debris removal as a function of pool elevation and type of armor would produce valuable measurements and observations that would contribute to the understanding of shoreline retreat. Long-range plans and evaluations of slope stability would be enhanced.

Wave Action

As already mentioned, removal of material at the base of a slope encourages slope failure. Although some slides empty almost instantaneously into the reservoir leaving very little debris at the reservoir edge, most landslides leave large amounts of debris. Removal by wave action is the main process of debris removal although boat wash very likely has a significant effect. Even low terraces experiencing skin slides and slow, headward retreat can have significant impacts on man's structures (Figures 9, 10, 18, 21, and 22).

The intensity of waves is controlled by the length and orientation of various valley segments, the number of high wind days, the intensity of the wind, the width of the valley, and the depth and the nature of the lake bottom. Wave action in the relatively narrow Spokane and San Poil River valleys is less intense than in the wider areas of the Columbia River. Perhaps partially related to more intense wave action, much of the valley fill material has been eroded from the lower Columbia River valley edges as well as certain river segments in the upper Columbia River valley.

The upper Columbia River valley has younger valley fill material and has less of its sediment removed. Therefore, it is experiencing more wave erosion and landslide activity at the present time. In particular, areas that project out into the reservoir or are at the end of a long fetch zone of the reservoir are particularly susceptible to erosion. A few of these areas are found in the Lincoln SE (NW ¼ Section 30, T28N, R36E),

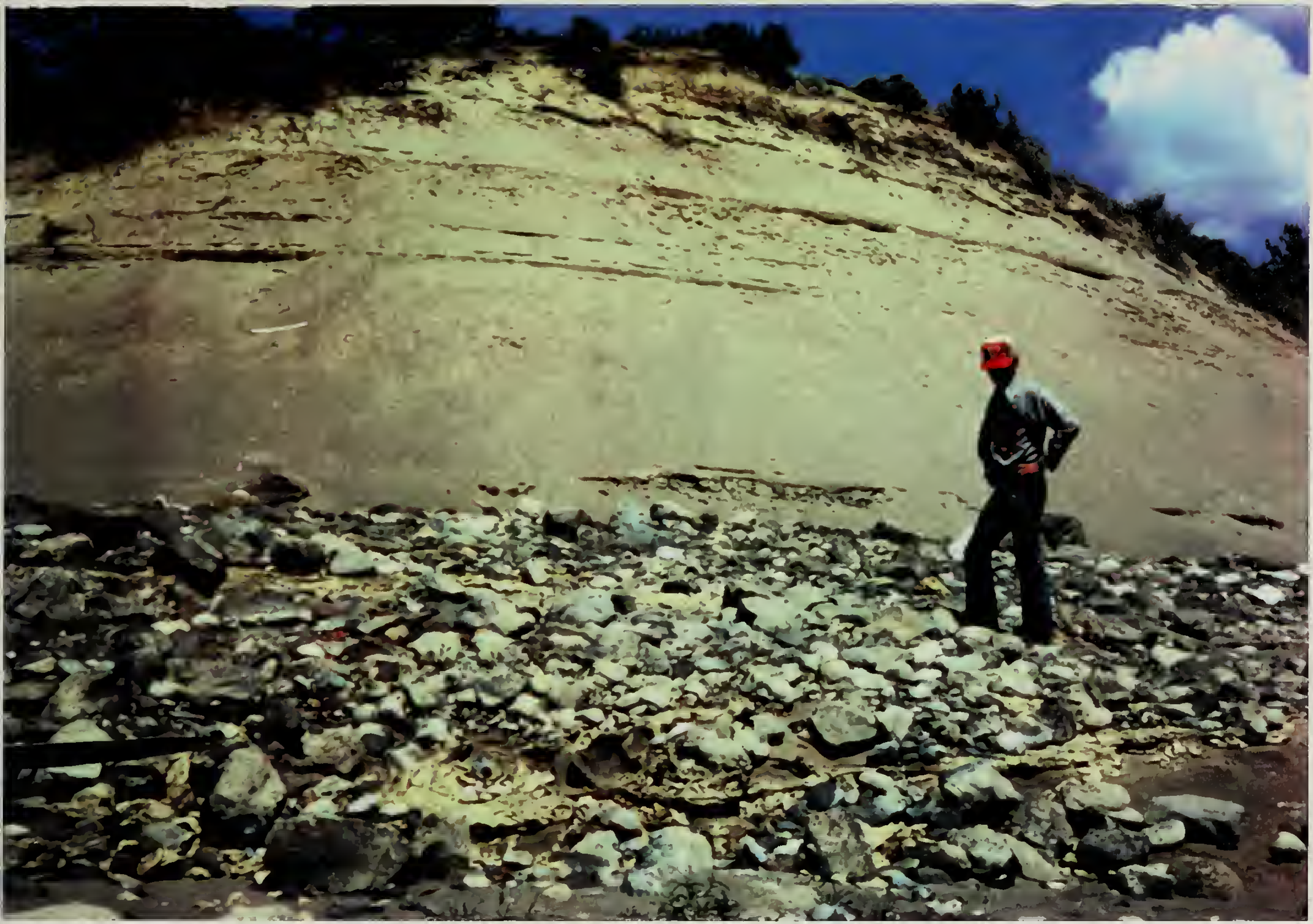


Figure 20 - Gravel armor in Seven Bays area. Lenses of gravel in Terrace sediments reduce slope retreat immediately offshore. Photo taken on 6/14/84.

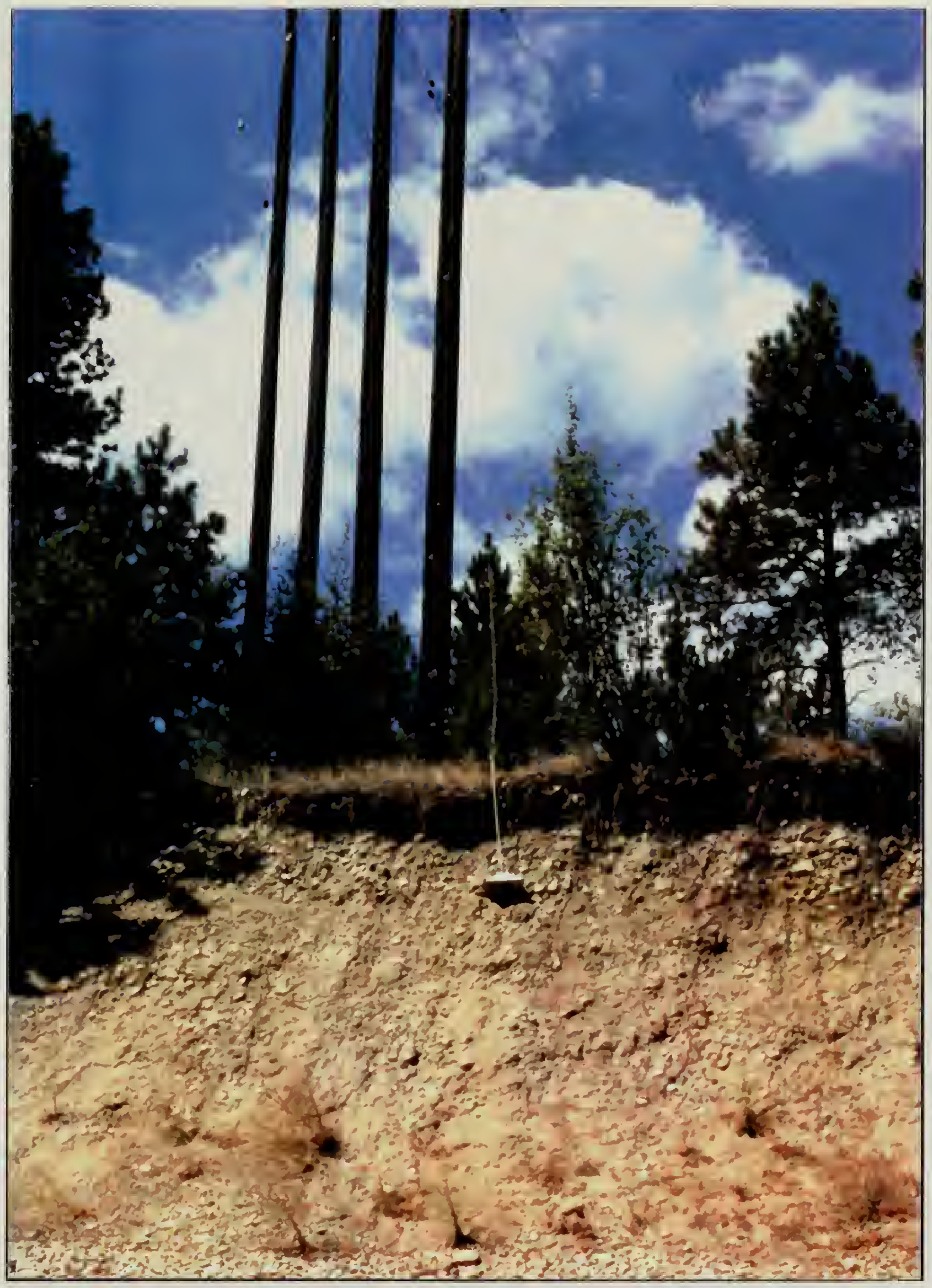


Figure 21 - Cement anchor loosened by slope retreat. Skim slides near the Kettle Falls bridge have loosened transmission line support. Photo taken on 7/24/85.

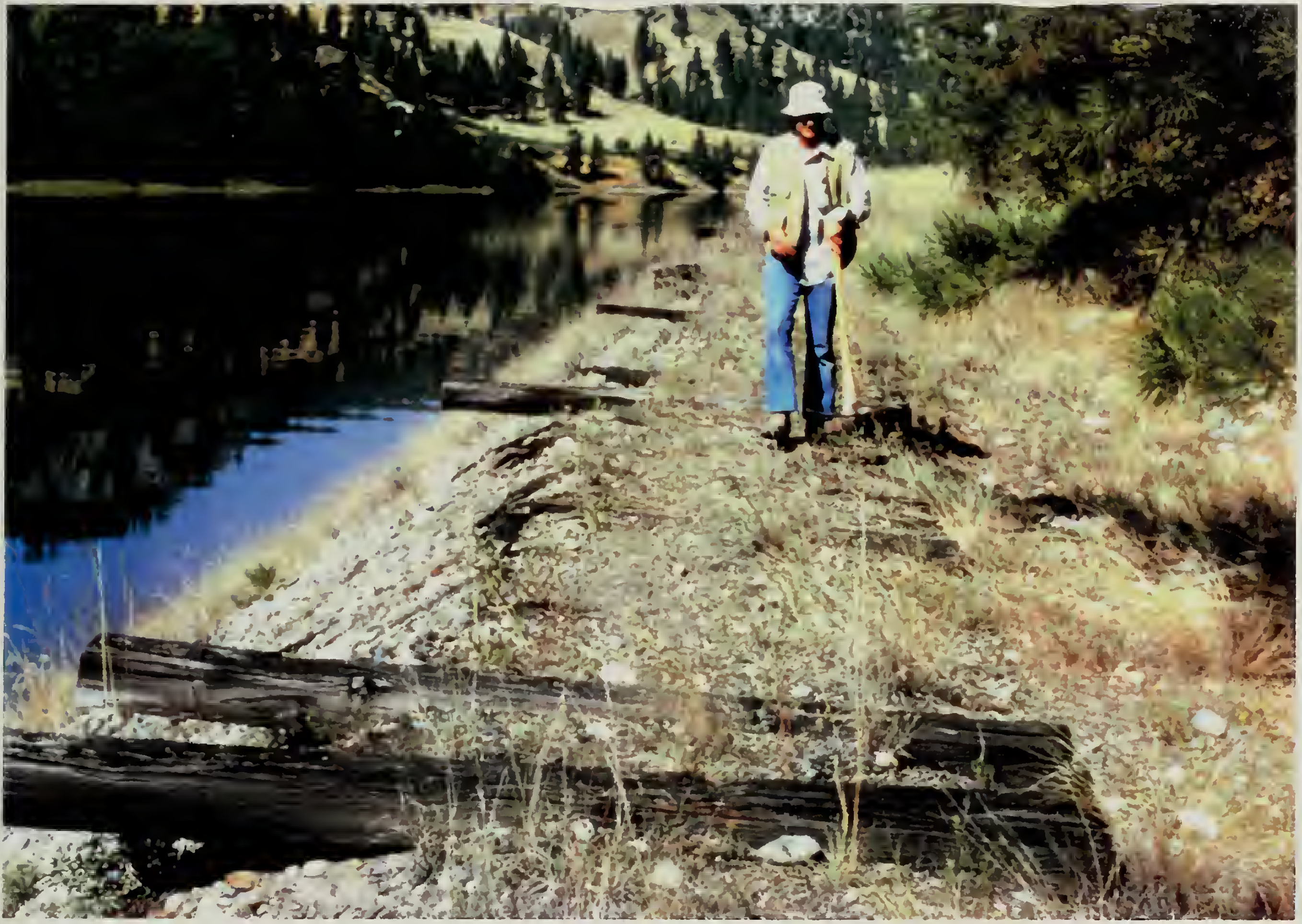


Figure 22 - Slope retreat causes railroad track abandonment (Sec. 8, T.38N., R.38E.; Bossburg quadrangle). Photo taken on 8/9/84.

Hunters (Section 35, T31N, R36E; Sections 5 and 8, T31N, R37E), Inchelium (Section 19 and 20, T34N, R37E), and the Marcus (Sections 22 and 23, T37N, R38E) quadrangles.

No systematic analysis of weather conditions, wave lengths and amplitudes, or other conditions was attempted but would provide some useful data in determining bank retreat rates and processes. Such data would also be useful to the National Park Service and their water safety responsibilities.

Lake disturbances caused by earthquake and landslides can produce seiche and lake waves. Such waves can be very large and could be highly destructive to buildings, boats, and people. Jones et al (1961, p. 18) reports waves up to 65 feet high crashing on the shore across from the Reed Terrace (Bangs Mt. 7.5 minute quadrangle) as a result of a 1952 landslide. Such a wave at the right location and at the right time could cause serious damage. If such a wave were generated across from inhabitated dwellings or campgrounds, especially when the reservoir were full, a serious condition could result. Topography along the reservoir bottom and the position of high terrace remnants have a considerable influence on the potential hazards.

Land Use

More intense use of surrounding lands for agricultural or residential uses increases the value of the land and places people in locations of greater risk. Although the probability of a given landowner or visitor experiencing property loss or physical harm is very low in most instances, over a period of time some property damage and physical harm to people is inevitable. The level of risk can only be determined after individual site evaluation and more data on slope retreat and landslide frequency and probability are available.

The construction of one house often encourages additional building and the maintenance of that settlement pattern for a long period of time. Thus the probability that someone will ultimately experience a particular hazard increases with time.

In addition to the passive risk of having property in a risk zone, or placing people into a risk zone, the risk often further increases because of these activities. Irrigation for domestic or agricultural purposes, septic tanks, gardens, etc., increases groundwater loading and often increases the probability of slope failure. Because of an expected high rate of growth, an area such as Seven Bays is one that has a high potential to magnify the probability of slope failure.

Slope Stability Under Earthquake Loading

The Lake Roosevelt area is included in the low risk zone according to the USGS seismic risk map. In spite of this designation, earthquakes are known to occur in and near the Columbia Intermontane Province. The 1872 North Cascades earthquake (Coombs 1976) in particular may have had impacts on this section of the Columbia River valley. If a similar event happened today, the amount of landslide activity could be intense. An earthquake study of north central Washington by Withers et al (1978) determined that a high seismicity area exists some 50 miles west of Grand Coulee Dam in the Chelan-Entiat area. The 1872 earthquake epicenter may have been near this area. Because we have such a short historical record to work with, it is difficult to precisely define the earthquake hazard or the recurrence interval for larger earthquakes. Recent work by Atwater (1994) and other workers suggests that magnitude 8.0 and larger earthquakes occur in coastal Washington and Puget Sound every few 100 years.

The effects of the 1872 earthquake on the Lake Roosevelt area are unknown without additional historical research, but it may have caused a few slope failures. Particularly suspected would be the Whitestone Rock area and the massive slump-flow rockslide on the east side of the town of Grand Coulee. The freshness of landslide morphology and the absence of substantial lichen growth on the bedrock or the rock clasts in the slide debris suggests very recent activity.

A similar earthquake occurring today could be easily modeled for the area and should be done as a separate project or as a part of a future detailed landslide study. The added stress due to ground movement would certainly affect those slopes that are close to their equilibrium conditions and perhaps some that are considered very safe under present conditions.

Overcompaction of Sediments

Loading of compressible sediments by ice or additional sediments can increase shear strength by increasing cohesion. After the ice melts or after erosion removes part of the overlying sediments, the actual strength of materials may exceed the predicted strength. The area near Kettle Falls definitely experienced an ice readvance which subjected the sediments there to extra load. Thus, sediments in this area are likely to be over consolidated.

Other ice positions recognized in the Columbia River valley appear to be stillstands rather than readvances and would, therefore, not have produced overcompacted sediments. Areas exhibiting contorted lacustrine sediments should be examined in detail for possible overconsolidation.

Slope Evolution

Systematic changes occur in the Lake Roosevelt area that operate on different time scales. The post-glacial history of the Lake Roosevelt area is a long-term change where a sediment-clogged valley (1700 feet and below) is gradually cleaned out. The build-up and gradual removal of material is described in the sections on terraces and bars. It is apparent from examining the geologic maps and looking at cross-sections across the Columbia River valley that perhaps less than 10 percent of the original valley fill remains in the valley.

A shorter term systematic change occurs along slopes that experience repetitious landslides. The time frame for the landslide cycle is variable and probably ranges from a few tens of years to hundreds of years.

Figure 23a shows a slope in unconsolidated materials prior to failure. In Figure 23b a slump-flow failure displaces material out into the reservoir where wave action, currents, and sub-reservoir mass movements carry debris away from the slope base. In Figure 23c the processes have removed much of the slide debris from the base of the slope and straightened the shoreline once again. Shear stress again reaches a critical value and new slides will occur removing old debris and eventually causing the crown to become involved in movement. Several areas affected by ancient landsliding occur along the Lake Roosevelt shoreline where major failure will likely occur again. The movements may be complex and old debris may never be completely removed before a new landslide cycle begins. Ultimately, this headward retreat will consume the terrace by scarp retreat back to bedrock or to the next highest terrace.

The duration of the cycle depends on many factors including the following:

1. Depth of water below the slope. If the near shore depth is great close to the slope that fails, nearly all of the debris may leave the slide scar area almost immediately exposing fresh material to reservoir processes.

2. Amount of slide debris.

3. Slope exposure to waves. If in a protected area, the time of the landslide cycle will be lengthened.

4. Amount and types of terrace armor.

5. Effects, if any, of earthquakes on triggering slides and mobilizing landslide debris.

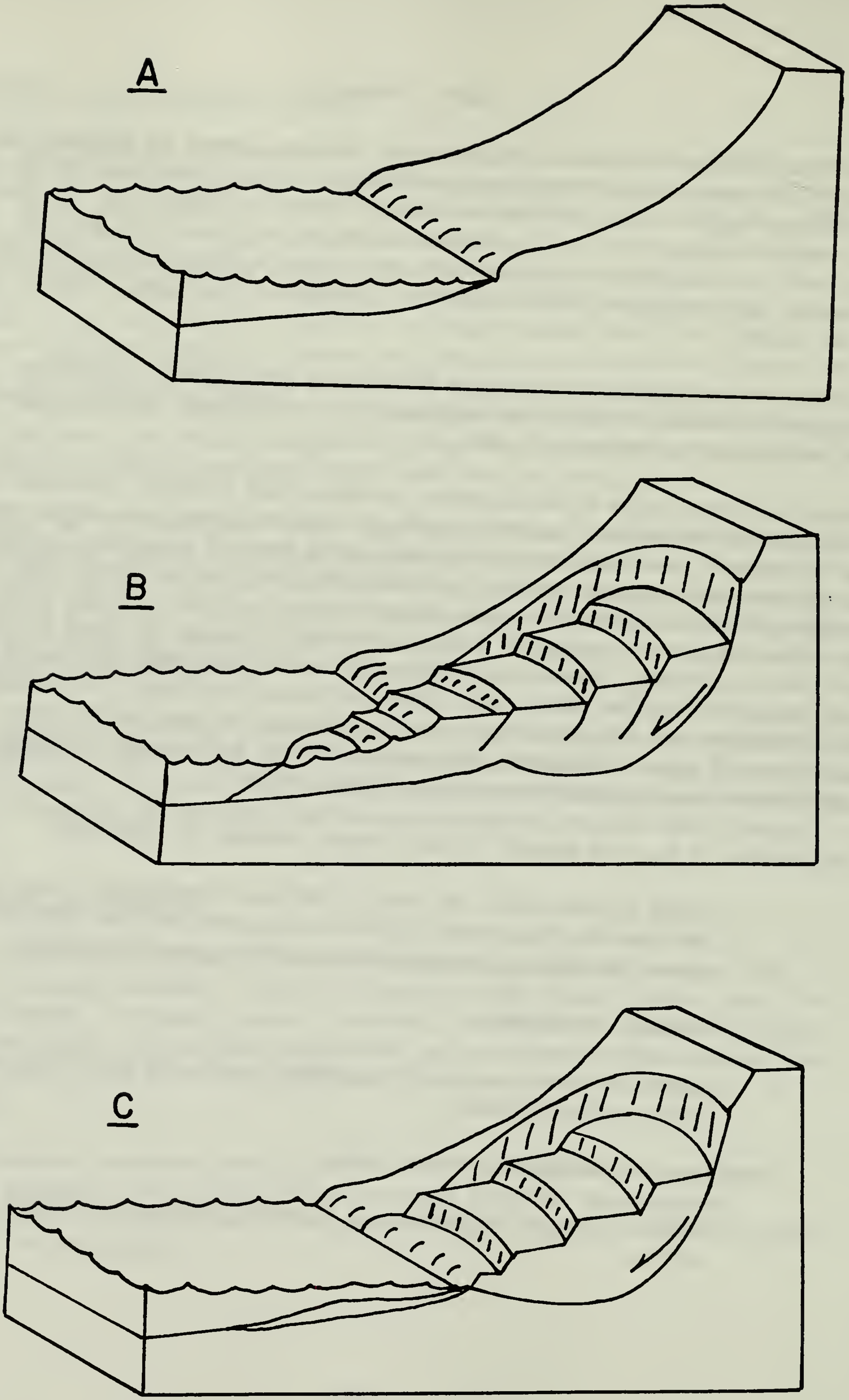


FIGURE 23, 23A, 23B, 23C - The Landslide Cycle Along Lake Roosevelt.

6. Precipitation.

7. Reservoir fluctuations.

8. Wave activity.

A number of different areas should be examined to determine rates of retreat. A wealth of information exists in old photographs. For example, the unconformity landslide at the mouth of Hawk Creek apparently started in 1941. A 1953 photograph (Jones and other 1961, p. 38) shows many differences with present conditions that could be described and probably be quantified. Other photographs in the same publication could be similarly studied.

Another aspect of the landslide cycle is that the terrace sediments occur in "steps" with lower terraces and alluvial slopes protecting and buttressing higher terraces. As these lower terraces and surfaces are consumed by landslide and other erosional activity, progressively higher terraces will be exposed encouraging larger, potentially more serious landslides.

The rate of slope retreat and the length of time for a landslide cycle in different areas would be useful information for long-range planning. Because one structure or house may encourage similar structures and establish a permanent settlement pattern, a safe distance back from today's reservoir edge may eventually be too close. With more data, policy makers can reasonably establish areas to be protected from development. Detailed studies of historic slides, slope retreat, and dating of sediments deposited in depressions on slide topography will permit more intelligent decisions to be made.

SUMMARY OF INDIVIDUAL QUADRANGLES

Introduction

Previous chapters of this report dealt with more general principles and features in the Lake Roosevelt area. This chapter attempts to concentrate some of these same and other observations into a geographic framework so that a general understanding of the geology of a given area of the reservoir is more readily accessible. This narrowing of concentration is intermediate in detail and should be followed in the future by summaries of even smaller geographic or terrace units.

Some more specific aspects, such as lineaments, that are not adequately discussed elsewhere in the report are also included here. The few observations about lineaments made here could be greatly strengthened and enlarged by more fully utilizing other imagery such as landsat, radar, U-2, orthophotoquads, and aeromagnetic maps. A detailed look at the bedrock geology would also be useful. In addition, lineament maps by Donovan (1983) and Sandness and others (1979) for this area and nearby areas are extremely useful and necessary for a comprehensive lineament study.

Orthophotoquads would make ideal base maps for a lineament analysis. An orthophotoquad of the Grand Coulee Dam 7.5 minute series quadrangle was developed as an example of the kind of lineamant maps that could be completed for critical areas along the shoreline. This drawing is appended to this report.

Grand Coulee (15 Minute) Quadrangle

The valley here, as in many other areas of Lake Roosevelt, consists of north-south and east-west segments. Prominent northwest and northeast structures actually control many of the north-south valley segments. The base topography for this 15 minute quadrangle has been updated and includes the Grand Coulee, Mica Mountain, Broadax Draw, and Jack Woods Butte 7.5 minute series quadrangles. These maps cover the area along the river from Elmer City past Grand Coulee Dam and to the upper Swawilla Basin near the east edge of the Mica Mountain map.

Millikan (1981) noted that the change in river course at Grand Coulee Dam is influenced by the Koontzville lineament. The Seaton's Canyon lineament controls the next up valley segment followed by the Electric City-Kwei Kwei Canyon lineament. Part of this latter lineament is obscured by overlying basalt flows.

The Elmer City-Hells Canyon-Meeker Mountain lineament partially controls the long east-trending valley segment on the east one-half of the quadrangle. The locations of some of these lineaments are depicted on an orthophotoquad of the Grand Coulee Dam 7.5 minute quadrangle appended to this report. Extensions of some of these lineaments go great distances and are shown on lineament maps by Donovan (1983). For example, the lineament north of Kwei Kwei Canyon is shown by Donovan as an extension of the large Sherman Creek Fault complex that bounds the east side of the Republic Graben.

The Seaton Canyon lineament seems to trend to the west footing of Grand Coulee Dam. However, the Seaton Canyon lineament intersects the Spring Canyon lineament and may terminate at that point. A pie-shaped piece of land occurs between the Seaton Canyon and Spring Canyon lineaments. Some of these are northwest trending features that parallel the low dip anticline trending towards Wilbur.

The maximum position of the late Wisconsin Okanogan lobe was near Neal Canyon where its front is marked by large boulders on land and water-lain till and outwash interbedded with lacustrine sediments in bluffs along the right bank of the reservoir. The ice front must have oscillated at least three times as recorded by layers of glacial gravel interbedded with lacustrine sediments. The gravel units often display foersts to the east indicating that they could not be flood deposits. West-dipping flood gravels in the same area overlie the glacial gravels. The sequence of events must have included glacial advance, retreat, burial by lake sediments, erosion of sediment as base level lowered, and very late floods.

The Grand Coulee section of the reservoir contains a good record of glacial lakes and also contains the upper end of Grand Coulee, the major base level control for glacial Lake Columbia II and III. Strandlines occur in widespread areas in the quadrangle but the best record is apparently near Peter Dan Creek where 2500 feet (762 m) pre-late Wisconsin and 2400 feet (730 m) late Wisconsin strandlines occur. The 2400-foot strandline is the highest late Wisconsin lake indicator identified along Lake Roosevelt. Lake sediments containing Glacier Peak ash near Spring Canyon indicate that Lake Columbia IV persisted to at least 11,250 years ago.

The Lake Columbia II terrace is well preserved in the Swawilla Basin and Spring Canyon areas where they are buttressed by lower terraces and alluvial slopes. In some cases the protection is minimal and slope retreat will produce steeper slopes with time (Section 9, 10, and 11, T28N, R31E; E ½ Section 5, T28N, R32E) and more potential for slope failure. Slide scarps are 5 to 15 feet high in the "Plum Point" (informal Reclamation name) area and will increase with time if shore erosion exceeds downwasting of slopes behind. Because land development is occurring in this area, some baseline data should be acquired as soon as possible.

The Kwei Kwei area has a wider strip of protection and should maintain stability for a longer time.

The 1360-foot (415 m) "Whitelaw Ranch" and "Woods Ranch" (Reclamation informal names) terraces (Sections 15 and 23, T28N, R32E) have intensive agricultural activity and slide scarps up to 40 feet high. Coarse flood gravels are common here although some interbedded lacustrine mud layers occur. Irrigation, groundwater perching, and spring activity occurs in Section 23.

A basalt slide area extends from the town of Grand Coulee eastward some 5 miles to Section 11. Some of the slides may date form the late 1800's (NE ¼ Section 13, T28N, R30E) and others predate Lake Columbia II sediments. Areas with granite outcrops on the lower slopes indicate that the critical unconformity between the granite and basalt is above reservoir level and therefore not threatened by reservoir processes. Unlike the Seven Bays area where the position of the unconformity could be below high pool elevation, here it is more likely that granite underlies all of the lower slopes. Thus, basalt slides induced by the reservoir are unlikely although slump-flow and unconformity slides from other causes such as seismic activity could occur in some of these areas.

An unusual feature in the Grand Coulee quadrangle is the Crescent Bay area. This isolated channel connects with the reservoir on the downvalley end but rises steeply upvalley into a granite channel. The channel may be caused by floodwaters that produced a retreating flood alcove that has completely removed the overlying basalt. If a large landslide blocked this former channel and deflected the river to a more northerly position as Ken Fox (USGS) reportedly suggests, one would expect to still find landslide debris blocking the channel. Rather, the channel appears clean of slide debris.

Wilbur (15 minute) Quadrangle

The updated topographic base maps for this quadrangle includes the Wilbur, Keller Ferry, Whitestone Rock, and Creston 7.5 Minute quadrangles.

As was true in the Grand Coulee 15 minute quadrangle, a structurally-controlled meander pattern characterizes the Columbia River valley here. The area extends from the upper Swawilla Basin to the south end of the Sand Hills and includes the lower end of the San Poil River valley. The locations of many of the structural controls are often obscure but the Spiegle Canyon-San Poil Valley and the Brody Creek-Whitestone Rock-Jump Canyon lineaments form major north-south controls. The latter lineament is related to the emplacement of the Lincoln gneiss dome to the east during late Laramide (Eocene?) time and controls the location of 4 miles of Columbia River channel.

Numerous smaller lineaments intersect the reservoir such as those at Wynhoff, Redford, and Hell Gate canyons. Intersecting lineaments also occur near the mouth of Penix Canyon. In some cases, such as at Hell Gate Canyon, the landslide cycle has been eliminated at the canyon mouth - perhaps the movement of groundwater along the lineaments and resulting accelerated rate of landslide activity has "cleaned" these areas out more rapidly than other areas.

No late Wisconsin glaciers occupied the Wilbur 15 minute quadrangle area although pre-late Wisconsin and pre-Wisconsin glaciers probably entered the area. Abundant small boulders in the Spiegle Canyon and Swawilla Basin area may have been deposited by older glaciers and were reworked later by Lake Missoula floods. The ridge of gravel (Devils Pasture - informal Reclamation term) behind the granite-cored island across from Spiegle Canyon (Section 19) is a pendant bar of flood origin (Figure 24). The position of these boulders about 13 miles south of the late Wisconsin ice margin, which is located near Brush Creek, is similar in separation to the pre-late Wisconsin and late Wisconsin ice fronts of the Columbia River valley lobe (Ft. Spokane area).

Old soils occur at about the 2400-foot elevation along Hell Gate Road (Brody Creek) suggesting that late Wisconsin flooding was below this elevation. The steeply dipping gravels at the mouth of Redford Canyon bury an old, interglacial soil and are in turn overlain by late Wisconsin lacustrine and flood sediments. Thus, a complex history of events has affected the Columbia River valley.

Strandlines of 2000- to 2200-foot elevation occur in the Spiegle Canyon area and Cochran and Warlow (1979) report strandlines up to 2400 feet in the San Poil River valley. Terrace elevations in the Wilbur 15 minute quadrangle are related to the major levels recognized elsewhere in the lower reservoir area. The sediments in the 1680- to 1720-foot Lake Columbia II terrace in the San Poil River valley were described by Atwater (1984; 1986) who recognized at least 15 major floods and perhaps as many as 89 recorded in the terrace sediments. Some current indicators in the 1400-foot terrace sediments record south-flowing floods that may have been derived from the San Poil River valley. Thus, not all of the recorded floods may be caused by the catastrophic discharge of glacial Lake Missoula.

Gravel caps are common but not ubiquitous on the lower terraces. Lake Columbia II terraces seldom have a gravel cap. The changing base levels caused downcutting and subsequent sliding of terrace sediments into the resulting eroded valley. Ice-contact slumping or ice over-ride cannot be the cause of the late Wisconsin landslides recorded in these sediments because the ice did not enter the Wilbur quadrangle during late Wisconsin time. A good exposure of an older landslide showing drag folding due to slide block movement occurs in the NW ¼ of Section 4 (T28N, R33E).

Unusual terrace remnants are found in the Sand Hills (right bank) and Penix Canyon (left bank) areas. Both dune-covered surfaces are about 1800 feet in elevation and have bedded lacustrine sand beneath. The Sand Hills surface may be partially a flood bar as suggested by its ridge shape and the existence of a flood channel next to the bedrock valley wall. The bedrock valley walls here have been scoured clean by floodwaters. Both of these massive deposits are in relatively protected point bar positions which may account for their development. Because the sands are of lacustrine origin, perhaps blockage of the Columbia River valley by the San Poil glacier during an older glaciation might account for backfilling to this level although no other terraces of this elevation occur in the lower reservoir area. An alternate hypothesis is that these areas are

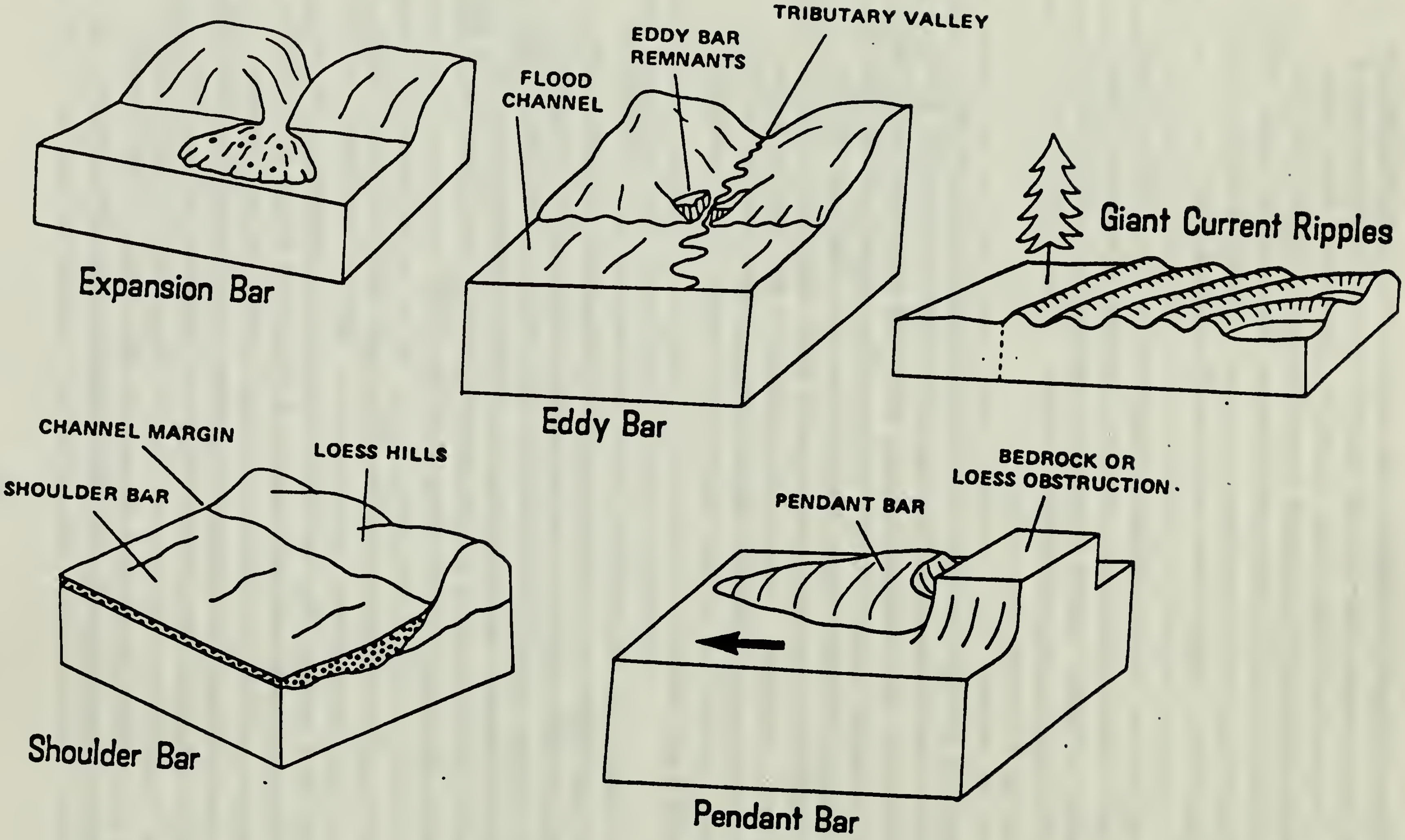


FIGURE 24 - Catastrophic flood bar forms (modified from Kiver and Stradling, 1982).

underlain by Lake Columbia II reminants overlain by 40 to 100 feet of flood deposits formed in a pendant bar location.

The light color of Whitestone Rock was noted by Lewis and Clark who named the monolith in the early 1800's. Exposed surfaces such as this in this climate usually become darkened by lichen growth after a few hundred years unless frequent spalling ormajor landslides clean it off. The large amounts of talus near the base of the structure suggest that such activity has occurred relatively recently at Whitestone Rock. A number of other light areas coincident with debris accumulation below are present on several exposed bedrock surfaces in other areas along the reservoir and indicate that some relatively recent rock slides have occurred.

A few large, older basalt landslides occur in the quadrangle in Sections 11, 12, 13, and 14 (T28N, R32E), in Sections 16 and 21 (T28N, R33E) and Section 8 (T28N, R34E). Because the lower end of the San Poil River valley was not cut until after the Miocene basalt eruptions, no Columbia River basalt could extend up into the San Poil River valley. The granite-basalt unconformity occurs everywhere above the maximum pool elevation in this quadrangle so that reservoir induced landslides from basalt are very unlikely.

Potentially hazardous areas occur where bedrock is not exposed immediately along the shore (to act as bedrock armor) and high terraces (1400-foot elevation or more) or very high groundwater conditions exist. However, some slopes above the bedrock rim may be hazardous and might fail from nonreservoir causes.

The lower San Poil River valley is the largest area of unstable slopes along the reservoir. Practically continuous slide scars line the reservoir edge here. High terrace landslides are common and are encouraged by the narrow valley and steep slopes along the San Poil River valley which were noted as far back as 1918 by Pardee. Also, locally high groundwater flow from irrigation and tributary valleys (e.g. 1984 Meadow Creek landslide) into the terrace also promotes slope failure.

An examination of the geologic map indicates that although a few areas have considerable distance to retreat back to bedrock in the San Poil River valley, many areas are in the early stages of bedrock exposure along the edge of the reservoir. A transition from slump-flow in wide terraces to unconformity landslides will occur in the future. Since little is known about rates of retreat under these different circumstances, it is difficult to predict whether slope activity will increase or decrease. However, regardless of activity rates, activity will certainly continue for many decades and probably much longer in the lower San Poil River valley.

The remainder of the reservoir edge still has some large areas lacking bedrock armor including the area south and northwest of the Sand Hills (Section 34), the Wynhoff-Penix

Canyon area, the terrace area east of the San Poil River (Sections 4, 9, 10, and 11), and the south end of the Keller landing terrace area (Sections 19 and 30).

Some of these areas such as the south Sand Hills (Section 34) and Penix Canyon areas only have narrow alluvial slopes protecting higher terraces from reservoir processes. However, the nature of the material in the surfaces behind seems to be mostly or entirely sand as observed in the few available exposures. If so, then skin slide activity will continue and large slump-flow activity is unlikely.

Relatively stable slope areas include all the bedrock areas and the Keller landing (left bank). The broad alluvial fan surfaces at Keller landing combine very stable slope conditions with unconsolidated material that is ideal for agriculture or construction purposes.

Some development is occurring in the Spiegle Canyon area and pressure to develop further may increase. The 1560-foot terrace (NE ¼ Section 30) is not desirable because of potential slope stability problems but the bluff in the NW ¼ Section 30 that has two houses on it may be safe because the underlying granite is close to the surface. However, unconformity slides will occur on the steep slopes and could cause some property loss although structural damage to the houses is unlikely.

Keller

Only the south half of the quadrangle was mapped with most of the emphasis on the southwest quarter along the San Poil River valley. This area is included on the updated Keller 7.5 minute quadrangle. The San Poil River valley originated during the Laramide Orogeny and was filled with San Poil volcanic materials during Eocene time (Pardee 1918, p. 44). Partial removal of volcanic materials has enabled the river to re-establish its path along its former course.

Major deformation first produced west- to northwest-trending faults and later (Eocene-Oligocene) north- to northeast-trending faults (Cochran and Warlow 1979) in the area. All of the major valleys follow these trends. The south-trending San Poil River valley is offset along one of these lineaments to the southeast near Jack Creek and to the southwest near Manila Creek.

The increased groundwater flow along lineaments and valleys has accelerated sediment removal at the mouths of most of the tributary valleys flowing into the reservoir. Bedrock walls occur on one valley wall at the mouths of Manila, Dick, unnamed creek in Section 5 by Mt. Tolman, Silver, and Meadow Creeks. John Tom Creek is the only tributary valley not cleaned out to bedrock on one valley wall. Even here a small outcrop of San Poil volcanic rock is exposed at the mouth indicating an early stage of sediment removal.

A major structural discontinuity occurs just north of the reservoir where the northwest-southeast trending valley segment by Keller is intersected by the Copper, Alice, Meadow, and Jack Creek lineaments. The intense mineralization of the granodiorite porphyry at Mt. Tolman may be genetically related to these lineament intersections. The Sclome-Freidlander Meadow lineament joins the 10-mile long Brody Creek-Whitestone Creek-Jump Canyon lineament (total length of 17 miles) in the Wilbur quadrangle.

Evidence of older glaciation is poorly preserved in the area. Deeply weathered bedrock surfaces begin at about 2400-foot elevation up Jace and Meadow Creeks and mark the upper limit of younger glaciers. Deep weathering profiles in the Freidlander Meadow area indicate that the glacial activity in this area is quite old - probably pre-Wisconsin in age.

A pre-late Wisconsin advance extended south of an intermediate age till near Silver Creek and perhaps to the Spiegle Canyon area in the Wilbur quadrangle. Large rounded boulders, one of which is 8 feet in diameter, occur at least up to 2050-foot elevation on the flanks of Mt. Tolman (Section 5 and 8, T29N, R33E).

The late Wisconsin terminus is placed near Brush Creek where large boulders occur on ice-contact surfaces (kame terraces). The terrace remnants grade from this location at 1840-foot elevation down to the 1700-foot Lake Columbia II terrace level.

Numerous terrace levels and terrace remnants are present in the San Poil River valley. In addition to the ice-contact surfaces at 1840-foot elevation in the north part of the quadrangle, Lake Columbia II (1680-1760 feet), Lake Columbia III (1560-1600 feet), and Lake Columbia IV (1360-1440 feet) terraces are also present. Elevation designations are more imprecise in the Keller quadrangle because of 80-foot contour interval of the base map used in this study.

The Lake Columbia II terraces are located back from the reservoir edge and the Lake Columbia IV terraces (approximately 1400 feet) line much of the shoreline in the Keller SW quadrangle. Large areas of bedrock armor occur on the right bank but an estimated 75 percent of the shoreline has landslide-vulnerable materials present. Wider terraces and more landslide activity occur on the left bank. Most of the landslides involve high terrace, large volume slope failures.

From the north end of the reservoir and past Keller to the Brush Creek area, old landslide scars rim the 1400-foot terrace extension. The landslide scars have a tree and dense vegetation cover which suggests that the landslide cycle here, away from the reservoir, has a long duration. Trees could be cored and a reasonable estimate of duration could be made for a non-reservoir site. A study of historical information for the same terrace to the south along the reservoir could achieve slope retreat values that would make an interesting comparison and would also help in long range planning.

The only large landslide to occur in this quadrangle since our study began was the Meadow Creek landslide on April 13, 1984. Contributing factors to this landslide included heavy rain, rapid spring snowmelt, low reservoir level (1265 feet), and the abundance of lacustrine mud which makes up most of the terrace thickness and extends beneath reservoir level. The configuration and depth of the reservoir directly in front of the failed slope may also have influenced the slide. A major factor was the position of two short, steep canyons directly behind the slide area where groundwater was funneled into the head of the landslide area.

Lincoln (15 Minute) Quadrangle

The updated topographic base maps for this area include the Johnny George Mountain, Lincoln, Olsen Canyon, and Fort Spokane 7.5 minute quadrangles. This area extends from Halverson Canyon in the west to about 5 miles east of the Spokane-Columbia confluence and northward up the Columbia Arm to the Miller Mountain area. The area is the most geologically complex area on the reservoir where glacier termini, catastrophic floods, and glacial lakes all interacted. The Jackson Springs landslide near Fort Spokane is the largest historic landslide along the reservoir. Development pressures in parts of the area are high and will be increasing in the future.

The Lincoln gneiss dome is structurally resistant and the river flows around it on three sides. A shear zone (Atwater and Rinehart 1984) partly controls the river location on the south and the Brody Creek-Whitestone Rock-Jump Canyon lineament controls the valley location on the west. The 11-mile long, north-south trending valley segment from Hawk Creek intersects the Nine Mile Creek lineament and is probably also controlled by the emplacement of the Lincoln dome. A major northeast-trending lineament controls the Spokane River valley from Ft. Spokane to its intersection with the major Mill Canyon-Enterprise Valley lineament in the Turtle Lake quadrangle to the east.

A complex of intersecting lineaments controls the position of Hawk Creek and Indian Creek in the Lincoln 7.5 minute quadrangle. Major tributaries to Hawk Creek such as Snook Canyon are also structurally controlled. The resulting large valley at Hawk Creek enables Lake Columbia II terrace sediments to extend some distance upvalley. As is true of many lineament-controlled tributaries, sediments are removed or partly removed at the tributary mouth. Sediments are removed to bedrock from the left bank at the mouth and are in the process of removal along one part of the right bank where an unconformity slide is occurring. The Hawk Creek area is one of the most active landslide areas along the reservoir.

Some of the lineaments that intersect the Columbia River valley are curved such as the North and South Forks of Three Mile Creek but most are straight and trend north-south and west by northwest. An extensive zone of north-south parallel lineaments at least 10 miles long and approximately 1-mile wide (best seen on an orthophotoquad) occurs along Whitestone Ridge and is associated with the Lincoln dome. The lineaments extend across the Columbia River valley into Sections 1 and 12 (T27N, R35E) where flood gravels partly cover them and basalt flows bury them in Section 12. Terrace materials are cleaned out where the lineaments intersect the reservoir edge (especially along the right bank).

The northeast-southwest trending Castle Rock lineament and the lineament in the unnamed tributary to the south are also cleaned out of terrace sediments. The mouth of Welsh Creek (north-south lineament) near Lincoln is making the transition from wide terraces to unconformity slides. The granite bedrock is presently exposed at one site at the valley mouth as well as in larger areas to the west and northeast. A nearby water well penetrates the sand and gravel deposits and enters the granite.

The glacial history in the area is complex. Although the evidence is somewhat sketchy, it is better than in other areas making this the best area for attempting to unravel the glacial history. Very old tills and other sediments are exposed along S.R. 22 in Sections 32 and 33 (T29N, R36E) and Sections 4 and 5 (T28N, R36E) and Sections 4 and 5 (T28N, R36E) at about 2400-foot elevation. Soils have well structured, argillic B zones and are highly oxidized. The downvalley extent of this ice is unknown. It must have blocked the Spokane River valley creating an older glacial Lake Spokane and probably terminated downvalley of Lincoln townsite.

The intermediate age till is found as a protected moraine along George Creek (Section 33, T28N, R35E) where it displays a subdued, but recognizable moraine topography. An intermediate age till on the left valley wall occurs at about 2000-foot elevation in Section 5 (T27N, R36E) and the downvalley extent of ice, estimated by projecting elevations and using the limiting position of the pre-Wisconsin Hawk Creek diamicton, is probably just upvalley of Hawk Creek. The China Camp Rapids, now beneath the reservoir, may be related to this former ice front.

The late Wisconsin(?) ice front maximum was near Lamb Draw (Rothlisburg school area) during the early part of the ice advance but retreated to the Castle Rock area as Lake Columbia rose in elevation. Till and kame deposits mark the Castel Rock ice position and abundant till occurs around the base of Miller Mountain.

Kame terraces reach 1840-foot elevation near the Castle Rock ice position and outwash gravels descend from the former ice front to the Lake Columbia II terrace level. Elevations of the Lake Columbia II terrace near Hawk Creek are as low as 1640 feet and may reflect a slightly lower base level of the bedrock lip of Grand Coulee. The group of terraces between 1640 to 1760 feet (locally higher close to an ice margin) are considered to be part o the same lake level even though a number of minor base level changes may be represented.

The Lake Columbia III (1560 feet) terrace level is prominent near Swede Flat and the Seven Bays area where it is 0.25 to 0.5 miles wide. The buttressing effect of lower terraces is significant near Seven Bays where the 1360-foot terrace is about 0.25 miles wide but it narrows considerably to the north in Section 1 (T27N, R35E). Removal of the terrace here will expose the higher terrace directly to the erosional effects along the reservoir edge. Fortunately, no development has occurred yet at this location.

The Lake Columbia IV (1400 feet) level is well buttressed by a wide remnant of the Lake Columbia V (1320-1360 feet) terrace in the Fort Spokane area. Farther up the Spokane River valley the buttressing is not present and considerable slope activity occurs along this segment of the shoreline. No bedrock armor is exposed so continued functioning of the landslide cycle is expected.

The Lake Columbia V terrace on the Spokane Indian Reservation is currently (1994) being developed into a destination casino resort. Depth charts of the reservoir show that this "low"terrace edge inclines steeply into the reservoir. Further, the depths contours indicate that a large submarine slide scarpt occurs below the casino site. Whether this slide scarp pre-dates or post-dates the reservoir is unknown.

The 1900-foot elevation Bockemuehl Canyon surface (Section 28, T28N, R36E) and its continuation (SE ¼ Section 31) above Swede Flats is unique to the Columbia River valley although similar elevation surfaces occur in the Spokane River valley. The surface is capped by stabilized sand dunes and underlain by sands of catastrophic flood origin. Part of the flat surface may be structurally controlled because of underlying basalt flows. The basalt/pre-Tertiary rock unconformity rises to the southeast towards Bockemuehl Canyon. Basal Latah beds underlie the basalt and at least one large landslide has occurred (W ½ Section 34, T28N, R36E). The flood sands may be derived from spillover through a flood pass at 2440-foot elevation on the south side of Lilienthal Mountain. An alternative hypothesis that this sediment could perhaps be a kame terrace deposit.

The basalt-granite unconformity slopes westward from the Bockemuehl surface towards Swede Flats where it is hidden by terrace sediments. The wide Lake Columbia III and other terraces hide the contact but it is likely below reservoir level. Water well logs and basalt outcrops at reservoir level occur about 1.25 miles southwest of Seven Bays indicating that the basalt-granite contact lies below the Seven Bays area. The unconformity is seen rising again at the town of Lincoln suggesting that there may be a basalt-filled Miocene Valley in this area.

No bedrock outcrops occur along the reservoir at and near Seven Bays including the areas along the numerous tributary valleys that flow into the reservoir here. These tributaries were investigated close to reservoir level but were not completely walked to see if bedrock is exposed farther away from the reservoir. Erosion in these valleys is uncovering older pre-terrace landslide debris which includes basalt blocks up to 12 feet (4 m) in diameter. Retreat of the lower terraces also acts to remove some of the lateral support for the valley wall behind.

Although the process of sediment removal usually takes appreciable time, man may speed the process up by adding considerable water onto upslope areas. Development is presently accelerating at several locations within the area, noteably at the confluence of the Columbia and Spokane Rivers, at Seven Bays, Hanson's Harbor, and Keller Ferry. All of these developments will add water to slopes and could disrupt the present equilibrium conditions. Additionally wave action, generated by increased boating activity on the lake, will accelerate toe erosion and under cutting of the terrace slopes.

No angular granite that might indicate the nearness of granite bedrock were noted in the Pleistocene age landslide debris on the slopes behind Seven Bays. A well in the SE ¼ SW ¼ Section 13, T27N, R35E at Seven Bays bottoms in broken basalt which further indicates that the unconformity is indeed below reservoir level in the Seven Bays area. Thus, the nature and location of the submerged contact, whether basal or interbedded Latah exists in this location, how much ground-water is present from natural and man-induced causes, and whether reservoir activity could induce slope failure should be investigated.

The area at the townsite of Lincoln has a formidable 300-foot basalt cliff immediately behind. There are pillow basalts and interbeds in the basalt section composing the cliff that could help induce a major slope failure here. The terrace remnant on which the town is built is less than 1000 feet wide and would be completely buried if a major slide occurred. Fortunately, the nonconformity between the basalt and the underlying granite is just above 1290 feet, the maximum elevation of the pool behind Grand Coulee Dam. Thus reservoir-induced sliding is unlikely where granite outcrops at reservoir level are present. Rock slides or falls, however, either through natural or man-induced causes, can result in large quantities of debris entering the reservoir and could generate a seiche or lake wave a few feet to tens of feet high. The effects of such a wave or waves would depend on reservoir level, time of year of failure, reservoir bottom topography, and other factors. The nearby Hawk Creek and Seven Bays areas are very popular and such a wave or waves could cause considerable damage to property and could result in fatalities or injuries.

Potential problems that need to be evaluated in the Seven Bays area involve the rate of shoreline retreat along the 1320- to 1360-foot terrace and the eventual removal of low terrace buttressing and exposure of the high terrace (1560 feet) to shoreline processes. Because of present and future construction that is planned, this area should be given high priority for future studies.

Other areas of possible concern are the Halverson and Van Leuven (informal USBR names) areas in Section 1 and 2 (T27N, R35E) and Sections 17 and 18 (T28N, R35E) downstream from Lincoln. These areas are being developed and slump-flow and unconformity landslides will occur in the future. Coarse, pendant bar gravels armor much of the Halverson surface but it is underlain by lacustrine clays and silts. The terrace appears wide here so that numerous landslide cycles could occur before bedrock is reached.

Some unusual features in the quadrangle include the Halverson pendant bar and other flood bars as well as giant current dunes (?) in parts of Sections 8 and 9 (T28N, R36E). A series of parallel, regularly-spaced gullies at this location seem to be best explained as giant current dunes formed by catastrophic flood processes.

The Jackson Spring (right bank) and Miles (left bank) landslides are in the Spokane Arm and located directly across from one another. The Jackson Spring landslide occurred during the spring of 1969 and was encouraged by groundwater loading and low reservoir levels. A sizable flow of water was issuing from the head of the slide the day after the landslide occurred.

Turtle Lake (15 Minute) Quadrangle

Updated topographic base maps for this area include the Turtle Lake, McCoy Lake, Inkster Lake, and Benjamin Lake 7.5 minute quadrangles.

The Spokane River flows southwest to the Bull Pasture (Cayuse Mountain) area where it loops broadly around to the northwest and eventually enters part o the pronounced northwest-southeast trending Mill Canyon-Enterprise Valley-Nine Mile Creek lineament (abbreviated MC-EV-NM). The river swings west at the south end of the Enterprise Valley and then flows southwest into the Fort Spokane 7.5 minute quadrangle. Numerous lineaments occur in the quadrangle but most are not shown on the geologic map.

The MC1-EV-NM lineament is an impressive 34-mile long northwest-southeast trending structure that controls the river valley location through most of the Turtle Lake quadrangle. The Enterprise Valley is a graben and San Poil volcanic rocks were extruded throughout its length during Eocene time. The Enterprise Valley is a hanging valley of broad dimensions whose history is related to major drainage changes of the Columbia River.

The broad swing of the river around the south end of Cayuse Mountain appears to be controlled by an intersection of numerous lineaments. The north-south trending Mill Canyon and a parallel, unnamed canyon 1.5 miles to the east are cut by a prominent northwest-oriented lineament that terminates near the mouth of Mill Canyon. The northeast-southwest valley segment on the east side of the map probably is structurally controlled and its extension can be traced through Matthew Lake on the adjacent quadrangle.

Terrace remnants are plentiful and have a much greater variety of elevations than those in the Columbia River valley. Terraces and lacustrine sediments up to 1920 feet occur in the Spokane River valley but not the Columbia River valley indicating that a local base level control was probably in effect. The Enterprise Valley glacier is believed to have been that control. Till on the south side of the valley up to 2400 feet supports the local ice dam hypothesis that helps explain terrace surfaces above the Lake Columbia II level (1700 feet). Base level must have lowered and eroded out some of the valley fill before the Lake Columbia II level and its associated sediments were deposited.

Some of the high sediments are flood derived and not tied to any base level. For example, the massive bar blocking the south end of the Enterprise Valley is glacial moraine reworked by later Missoula floods. Ice must have occupied the Enterprise Valley and McCoy Lake depression during flooding since no evidence of major flood waters flowing through the valley or any flood sediment fill in the McCoy depression is apparent.

Numerous Lake Columbia II remnants occur along the reservoir including those near the Enterprise Valley, Sand Flat, and the Bull Pasture (Cayuse Mountain) areas. Lake columbia III remnants are particularly abundant and are composed of rhythmic flood sediments with clay interbeds. At least 10 flood units are exposed in the Blue Creek area. Locally there is a flood gravel cap but most terrace remnants have eolian sediments over lacustrine mud and flood sands. The potential of large slides from this terrace is high.

Pre-late Wisconsin glaciers were more extensive than late Wisconsin glaciers but the evidence is mostly destroyed by subsequent events. Boulder accumulations in the Sand Flat area are believed to be reworked moraines of pre-Wisconsin and perhaps late Wisconsin ages. Ice flowing through the Enterprise Valley and down the Columbia River valley joined in the Ft. Spokane area during pre-late Wisconsin time and reached at least the 2400-foot elevation level leaving Miller Mountain and the high granitic areas west of McCoy Lake as nunataks.

Late Wisconsin ice was less extensive but probably reached the south side of the valley creating another glacial Lake Spokane. Late Wisconsin(?) whaleback forms and scoured bedrock surfaces occur upstream of the Blue Creek area. The downstream extent is unknown, but the large boulders that armor the meander necks projecting into the reservoir in the Lincoln NE quadrangle may represent moraines reworked by floods.

The Spokane River valley is the main pathway for Lake Missoula floods. The concentrated flow kept many surfaces relatively sediment free although deposition occurred in favorable sites such as those behind bedrock hills. The top of Pitney Butte (2600 feet) has a late Wisconsin age soil indicating that the surface was scoured by some of the late Wisconsin floods. Floodwaters also spilled up Hollies Creek, through the pass on the east side of Lilienthal Mountain, onto the Bockemuehl Canyon surface (Lincoln quadrangle), and then into the Columbia River.

No Columbia River Basalt outcrops are close to reservoir level and no large basalt landslides were noted. Much more abundant in this area are the San Poil volcanics that are concentrated along the Enterprise Valley graben and its extensions. Only small rockslides, such as the one in the SE ¼ of Section 8 (T28N, R37E) are present. No large landslides are associated with this lava even though its major characteristics are similar to those of the Columbia River Basalt. The difference may be that no Latah-like sediments are interbedded with the San Poil volcanics to provide the necessary weakness to cause slope failures.

High terraces fronting directly onto the reservoir or protected by a very narrow terrace or alluvial slope are common along this section of the reservoir. In some cases, such as the high terrace near Orazada Creek, large landslides are not in evidence although a number of low slide scarps (10 to 12 feet) are present. The combination glacial flood and lake deposit at the mouth of the Enterprise Valley seems to be very sand rich providing good drainage and high stability. However, fine-grained lacustrine sediments are at least locally present along the lower slopes and the possibility of large landslides here cannot be ruled out.

The Detillion terrace (informal USBR terminology) in Section 12 (T28N, R36E) has an upper elevation of 1480 feet and narrow alluvial slopes that are protecting the higher terrace. However, the slow retreat of the alluvial slopes will eventually expose the higher terrace to shoreline processes.

The Pitney Butte area has steep alluvial slopes descending from the 1560-foot lacustrine terrace to the reservoir. Landslide activity is locally important on upper slopes of the terrace where surface wash sediment (colluvium) is thin. No large landslide scars were noted on the lower slopes where colluvium is thicker. A number of summer houses are built on these alluvial slopes (SW ¼ Section 17, T26N, R36E) so that slope activity in this area could have serious consequences.

The 1600-foot terrace in the Sand Creek area (SW ¼ Section 17, T28N, R37E) lacks any buttressing material except for recent slide debris. This high terrace area is extremely unstable but does not threaten any structures. The San Poil volcanic rock is about 600 feet behind the landslide crown.

At the mouth of Sand Creek to the south, terrace material is partially cleaned out and the creek is superimposed onto a mass of San Poil volcanic rock. The Sand Creek lineament apparently connects with the Hollies Creek lineament directly across the Spokane River valley. The 1360- to 1400-foot terrace at the mouth of Hollies Creek is about 1500 feet wide and has active landslides along its perimeter.

The Sherwood Mine area near Blue Creek has lacustrine and flood sediments up to 1900-foot elevation with approximately 100 feet of overlying uranium mine tailings. The sand-to-clay ratio is quite high and no large landslides are present except for one in the

Blue Creek Bay (NW ¼ Section 34) and an unconformity slide to the southwest that dates from the late 1800's (Jim LaBret, personal communication). Blue Creek to the north follows an arcuate lineament.

Sand flows have moved down the steep slope below the mine into the reservoir (SW ¼ Section 34) and a large landslide would bring the uranium tailings into the reservoir, thus introducing radionuclides, heavy metals, and landslide debris. Seepage of such contaminants by surface and ground waters may be occurring at present. The report by Chleborad and Schuster (1984) describes the physical environment and risks related to this particular slope.

The Sand Flat area is a stepped terrace area nearly 1.5 miles wide associated with an unusually narrow river channel. The narrow channel is attributed to the abundance of very large boulders, presumably a lag deposit left after floodwaters reworked a glacial moraine. Slope retreat is very slow here because of the effective boulder armor. The width of the terrace complex, the presence of a number of lineaments leading onto the terrace surface, and the lack of abundant surface drainage suggests that potentially high volume groundwater conditions exist here. The Green Canyon lineament and the lineaments following the unnamed valleys 2.5 and 3.5 miles to the south lead directly onto the 1560- and 1880-foot terraces.

The possibility of a buried channel in the Sand Flat area is also very high because of the thickness and width of terrace material. Alcoves where rapid slope retreat is occurring are likely sites for buried channels or locations of high groundwater discharge. The Sand Flat alcove (SE ¼ Section 15, T27N, R37E) has a high volume spring discharge on its south side. The lower buttressing alluvial slopes and low terraces have been removed exposing the 1600-foot terrace directly to the reservoir. This massive alcove is located immediately upvalley from the giant lag boulders that mark the former position of the Enterprise Valley lobe.

Another major alcove occurs in the NE ¼ Section 36 (T27N, R37E) at the mouth of Harker Canyon where slope retreat has exposed a 1760-foot high terrace. The slide scarp is about 110 feet high and is oldest (some vegetation cover) on the north end and younger on the east. San Poil volcanic rock occurs at or near the "tails" or edges of the slide scar but no bedrock is exposed in the scarp center. Thus, considerable slump-flow retreat may occur before unconformity slides begin. The drainage is anomalous here with Harker Creek flowing into the reservoir in a valley separated by a narrow ridge from the landslide scar.

The Bull Pasture (Cayuse Mountain, USBR name) area is near a prominent, gentle bend in the river where a number of lineaments intersect. The stepped terrace area is quite broad, about 1.25 miles wide, and has terraces at 1800-, 1700- (the most extensive terraces), 1640-, and 1360-foot elevations. An extensive irrigation project on the

Spokane Indian Reservation land utilizes these terrace surfaces. The edge of the terrace is locally buttressed by alluvial fans, alluvial slopes, and the 1360 terrace.

On the southeast side of the terrace complex in the N ½ Section 32 and SW ¼ of Section 28 (T27N, R38E) the buttressing material is mostly removed and an estimated 400-foot landslide scarp faces the reservoir. Mostly skin slides are occurring because of the high ratio of sand to clay. However, clay units are present and a large volume slump-flow landslide is possible.

In the Mill Canyon area a number of houses have been constructed. Most are built on alluvial slopes and are relatively safe from landslide hazards. One house in the SW ¼ of Section 31 (T27N, R38E) is on a small remnant of a 1440-foot terrace underlain by lacustrine mud that is not buttressed along the reservoir. A relatively fresh landslide scarp faces the reservoir below the house. Another house in the SE ¼ of section 32 (T27N, R38E) is built on thin alluvium overlying lacustrine muds (Figure 24). A small landslide scar about 15 feet high indicates that slope retreat is progressing and may eventually threaten the house.

The Tamarack Canyon (USBR name) area (Section 22 and 27, T27N, R38E) has a 1720-foot terrace along the left bank that has flood gravels overlying flood sands with interbedded lacustrine muds. The valley is very narrow here and a medium size landslide could block the entire river.

Little Falls (7.5 Minute) Quadrangle

The Spokane River valley extends from the west edge of the map to the Little Falls Dam which is located about two thirds of the way across the quadrangle and ends on the east where Little Chamokane Creek joins the Spokane River.

Lake Roosevelt essentially ends just below Little Falls Dam. The valley is quite narrow and the width of the reservoir is about 150 feet. The river is inset into a deep canyon cut mostly into the Lake Columbia IV (1400 feet) terrace. The valley contains considerable sediment and probably resembles the Columbia River shortly after the glaciers and glacial lakes had disappeared. The smaller Spokane River has removed a smaller proportion of its sediment fill than the Columbia River.

No orthophotoquads were examined so that some lineaments were undoubtedly missed. The Matthews Lake lineament appears to control the northeast-southwest valley segment that extends downvalley to the Bull Pasture (Cayuse Mountain) area. A N80W trending valley segment to the east of the Matthews Lake lineament continues upstream for 2.5 miles and a northeast segment extends to the granite foundation of Little Falls Dam.

Northeast trending lineaments occur along Tamarack Canyon and from near Little Falls Dam towards Little Chamokane Creek. North-south lineaments occur along Little

Chamokane Creek and its extension along the Spokane River and along Spring Creek in the southwest ¼ of the quadrangle. However, no major cross lineaments seem to intersect the reservoir although short, steep canyons do lead to the marginal terraces and undoubtedly supply some groundwater to the system.

Pre-Wisconsin glaciers affected the area but late Wisconsin glaciers were much farther north. Local accumulations of large boulders in flood gravels just east of the quadrangle and in a gravel cap at about 1700 feet in Section 22 (T27N, R38E) are probably reworked glacial deposits. Some of the boulders exceed 3 feet in diameter. Some striated rocks were found in association with the boulders just east of the quadrangle and a paleosol is on top of the boulder deposit in Section 22.

Catastrophic flood currents were very effective in forming flood bars in this area. In addition to the main flood current down the Spokane River, floodwaters farther north crossed a divide that allowed water to flow into the Colville Valley and south along its continuation in the Chamokane Creek valley. A scabland topography occurs in the basalt terrain in the Matthews Lake area (Section 7 and 8, T27N, R39E). Scoured depressions in bedrock and a dryfalls at Matthews Lake indicate that the flood water surface exceeded 2400 feet. Pendant and shoulder bars (Figure 24) are abundant and two areas of giant current dunes occur south of the river. The flood sediment is interbedded with lacustrine clays and silts so that landslides should be considered in dealing with this landscape.

The 1400-foot terrace lines the reservoir almost everywhere in this quadrangle except in parts of Sections 14, 15, and 22 where granite is exposed and in the SW ¼ Section 19 and 20 (T27N, R39E) where the 1700-foot terrace occurs immediately adjacent to the reservoir.

The abundance of valley fill material and the abundance of bedrock outcrops along the river near the Little Falls Dam suggest that some buried channels might be present and the river was superposed on the bedrock that now forms the footings of Little Falls Dam. In particular, the broad 1700-foot elevation surface in Sections 20, 21, 28, and 29 (T27N, R39E) may cover a former river channel. If a buried channel exists, the downvalley end would likely be where the 1700-foot terrace in Section 19 and 20 towers above the reservoir. Springs in this area could also be the result of a buried channel.

Basalt is exposed well back from the reservoir edge in the Little Falls quadrangle. Large, post-glacial basalt landslides occur along Spring Canyon and in Section 4 in areas located away from the reservoir.

Practically continuous, recently active landslide scars occur along the reservoir perimeter in the Little Falls quadrangle. More stable areas exist where streams have graded slopes back (Section 14 and north of Spring Canyon) or alluvial fans have built along the reservoir (NE ¼ Section 24). Irrigation is locally important and groundwater perching is in evidence. A major landslide here could temporarily close off the Spokane River. The storage capacity in this narrow segment of the reservoir is not large so that water backing up could threaten a number of homes and also the facilities at Little Falls Dam. Depending on water flow conditions and storage capacity behind upriver dam, the amount of time available to deal with rising water levels in this short segment of valley could be rather short.

Wilmont Creek (15 Minute) Quadrangle

Updated topographic base maps for this area include the Gold Mountain, Nine Mile Flat, Miller Mountain, and Kewa 7.5 minute quadrangles.

The Columbia River valley here extends from the Castle Rock area (Lincoln quadrangle) northwestward along the Nine Mile lineament, it then follows a northeast trend along one segment of the lower Wilmont Creek lineament, trends eastward, and then trends north along the Nez Perce-Enterprise Valley lineament to the Hunters area. Near Hunters, the valley trends eastward along the Coyote Creek lineament.

A very noticeable increase in reservoir width occurs in the Nine Mile area where the Nine Mile lineament, Canteen Creek, and Little Nine Mile Creek lineaments intersect. This exceptionally wide zone was originally created by more effective erosion along these structurally weak zones. The present, rapid rate of removal of valley fill material in the Nine Mile area due to landslides serves to emphasize this anomalous valley width.

The east to southeast trending valley segment from the "The Slide" area (Section 35, T30N, R35E) follows the O-Ra-Pak-En Creek lineament and parallels the lower Wilmont Creek lineament in Section 31 (T30N, R36E) and adjacent sections. Most of these lineaments are not shown on the geologic maps but should be placed on separate orthophotoquad maps or overlays and should be related carefully to lithologic contacts, structures, and other features shown on the appropriate geologic maps.

A number of northwesterly trending lineaments intersect the northerly trending segment of the Columbia River valley including one that passes just south of Rogers Bar school and Monoghan Creek. A number of east-west lineaments occur along the prominent ridge in Sections 7, 8, and 9 (T30N, R36E) and along Coyote Creek, Middle Mountain, and Falls Creek. The lineaments parallel others in the adjacent Hunters quadrangle and intersect in the Nez Perce Creek area where another unusually wide valley segment and a large quantity of valley fill material occurs.

The Wilmont Creek area is north of the late Wisconsin ice terminus but far enough south so that the position of the pre-late Wisconsin (intermediate age) and the late Wisconsin(?) Lamb Draw ice margins are still distinguishable by moraines and till outcrops. Slightly oxidized soils containing some weathered rock clasts are intermediate in age. Soils oxidized to a red-brown color with argillic B horizons and good soil structure are pre-Wisconsin in age and occur on higher surfaces. Both pre-Wisconsin and pre-late Wisconsin soils occur on Miller Mountain which was a nunatak during late Pleistocene glaciation. Pre-late Wisconsin till and lake deposits also occur on Miller Mountain. Evidence of the late Wisconsin Castle Rock ice position is well recorded by moraines and kame terraces in the Nine Mile and Miller Mountain areas.

Terraces include the widespread Lake Columbia III (1560 feet) and Lake Columbia V (1320 to 1360 feet) levels. The Lake Columbia II water level decreased to a lower level shortly after ice retreated from the Castle Rock ice position. Sediments of Lake Columbia accumulated in front of the retreating ice but did not have time to reach the 1700-foot level north of Castle Rock before base level at the Grand Coulee lip was reduced. Because of the quadrangle location, the late Wisconsin ice front, kame terraces, and other ice contact surfaces are common within this quadrangle. These surfaces tend to be relatively high and have steep slopes facing the former glacier which encourages slope failure after ice retreat. As the ice retreated, lacustrine and flood sediments filled the vacated valley and built up to the Lake Columbia III terrace level that helped buttress higher, potentially more dangerous ice-contact terraces.

The flood sediments in the O-Ra-Pak-En Creek area locally show ripple-laminated sands deposited by both upvalley and downvalley currents. A downvalley flood may have originated from either Missoula floods flowing northward through the Enterprise Valley and then south in the Columbia River valley or a locally-derived outburst flood from farther up the Columbia River valley may have occurred. At least 10 flood units separated by varved lacustrine mud layers occur near O-Ra-Pak-En Creek.

The high kame terraces are potentially hazardous because of their high relief above the reservoir and the presence of lacustrine silts and clays. The Miller Mountain ice-contact surface (Section 13, 14, 23, and 24, T29N, R35E) is in the process of terrace narrowing by landslide retreat. Old scars occur on the terrace edge and landslide blocks occur on the slopes. Second cycle landslides occurring along the edge of the reservoir are moving former landslide material and undisturbed terrace sediments as well. Farm roads that paralleled the shoreline have slid out at a number of locations and are no longer passable. The duration of the landslide cycle here is unknown but the higher landslide scarps are pre-reservoir. Agricultural use of the land on the terrace top is occurring now but pressures similar to those that helped create the nearby housing developments to the north could eventually affect this area.

In addition to valley widening from the Miller Mountain terrace, slope retreat directly across the valley at Nine Mile Flat also contributes to the unusually wide valley here. Nine Mile Flat is at 1900-foot elevation and has considerable amounts of fine sediment layers in the section. Landslide scars at the upper edge of the 1900-foot terrace are pre-reservoir in age. Both slump-flow and multiple alcove landslides are recognizable.

The prominent landslide called "The Slide" on the topographic map (Section 35, T30N, R35E) had a major movement in 1906 although even older movements had affected the same area (Jones and others 1961, p. 21). The 1906 slide apparently blocked the Columbia River for about 45 minutes.

Nine Mile Creek locally flows over bedrock ridges in rapids and waterfalls indicating that the channel has been displaced from its original position and the creek is now locally superposed. It occupies a position on the far west side of Nine Mile Flat leaving most of the area of Nine Mile Flat without surface drainage.

A break in slope at about 1600 feet first recognized by Jones and others (1961) was interpreted as a wave-built bench due to temporary damming of the river at this level. They do not elaborate how this ties in with the general history of the area but the bench is best explained as a result of base level lowering at Grand Coulee near the end of glaciation and is probably tied in with Lake Columbia III. This minor terrace remnant is recognizable in the field but cannot be identified on the topographic maps because of its narrowness. Although it is not a major feature and is only locally present, it is significant in that active sliding occurring on the lower slope will eventually destroy this narrow terrace remnant and the higher terrace will then loom above the reservoir.

The Wilmont Creek and Nine Mile Creek valleys contain kame terrace deposits. A 2080-foot level is recognizable as well as remnants at lower elevations near the valley mouths. These levels formed as ice thinned during retreat of the Columbia River lobe. At least three different lineament directions are recorded by segments of Wilmont Creek. The location of the buried channel is not precisely known but is in Section 1 (T30N, R35E) or Section 6 (T30N, R36E).

Buttressing by the 1320-foot terrace occurs along the reservoir edge at Wilmont Creek except for the area near "The Slide" and in Sections 32 and 33 (T340N, R36E). As slope retreat progresses, the higher surfaces, similar to that by "The Slide" will be exposed to reservoir processes. Unconformity slides are beginning to occur in areas where bedrock is now starting to be uncovered.

Hunters (15 Minute) Quadrangle

Updated topographic base maps for this area include the Hunters, Adams Mountain, Blackhorse Canyon, and Cedonia 7.5-minute quadrangles.

The Columbia River valley follows the north-south trending Nez Perce-Enterprise Valley lineament and turns northeast just north of Hunters where it follows the Coyote Creek and Middle Mountain-Harvey Creek lineaments. The valley continues north for about 4.5 miles where it veers to the northeast again and joins the Inchelium 15 minute quadrangle at the north edge of the map. Northwest and northeast trending lineaments are abundant and at least two major north-south zones exist where the Columbia River valley is similarly oriented. A wide zone of parallel north-south trending lineaments (bedding planes?) occurs east of and parallel to the Columbia River in Sections 3,4,9,10, 15, 16, 21, and 22 (T31N, R37E). Glacial flow has emphasized these structural weaknesses and produced an impressive series of whaleback landforms.

A few east-west lineaments occur including Hunters Creek, the large Paleozoic rock ridge to the south, and Harvey Creek. Two prominent lineaments marked by a rock cliff and a narrow valley 1 to 2 miles east of the river begin just north of Cedonia and follow the valley northeast of Clark Lake. A prominent arcuate lineament trending approximately east-west extends through the Fruitland area. An analysis of these lineaments should be done as a separate project and should combine parts of both the Hunters and Wilmont Creek quadrangles because their boundary cuts through the axis of the river. Again, many of these lineaments are not included on the geologic maps because of time limitations and concern for too much detail on the maps.

The south flowing Columbia River glacier split at the south end of the map area with one lobe turning west to follow the Columbia River valley but the major ice flow continued south into the Enterprise Valley. Lateral and terminal moraines mark the late Wisconsin Lamb Draw and Castle Rock ice edges in numerous areas including the Mudgett Lake area. A prominent terminal moraine also exists in the Turk (Section 35, T30N, R38E) area. Lower lateral moraines and kame terraces mark recessional positions of the glacier.

Above the late Wisconsin ice edge are intermediate and old soils that help delineate the former extent of older glaciers in the area. Patches of till and lake sediments along the south fork of Hunters Creek mark the edge of the intermediate(?) age glacier. Interestingly, this site located high above and well back from the reservoir shows active landsliding because of the characteristics of the fine-grained lacustrine material.

Evidence for catastrophic floods this far north is not strong. Undoubtedly, some of the plane-bedded sands along the edge of the reservoir are flood derived but they lack strong supporting features such as rip-up clasts, etc., because of their distance from the main flood channel along the Spokane and Columbia River valleys.

Landslides mostly occur in the numerous terrace remnants along the reservoir. Most of these remnants are from local kame terraces although extensions of Lake Columbia III, IV, and V occur in the area. Landsliding in lacustrine sediments are overlain by undeformed lacustrine sediments indicating that landsliding was contemporaneous with deposition (e.g., Section 17, T31N, R37E).

The area from O-Ra-Pak-En Creek (left bank) northward to Section 35 (T30N, R36E) is potentially hazardous because of the abundance of lacustrine material in the terrace. No large landslide scars are present but small, continuous slope failures exist up to the first outcrop of San Poil volcanic rock in Section 36. No buttressing exists at the base of this slope in this section. Unconformity slides are beginning north of this point.

The 1520-foot surface farther north in Section 13 and 24 has no significant buttressing and is retreating rapidly. The terrace is broad here, nearly 0.75 miles across, and is used almost exclusively for agriculture at the present time. This could be a problem area if other types of development were to occur. The position of the preglacial Hunters Creek drainage is unclear in this area. However, a buried channel may occur in the Section 13 area.

Unstable slopes occur in Section 31 (T31N, R37E) farther north (left bank) where the Hunters ice position is marked by lacustrine sediments overlying a cobble-rich till (Figure 5). Numerous springs emerge at this location and heavy irrigation is occurring in the alfalfa field behind on the 1560-foot terrace. The terrace narrows here to about 1700 feet wide and the main S.R. 22 is located on the upper part of this terrace. An incipient scar or crack in the upper slope suggests that some slope adjustments may be in progress now.

The Nez Perce Creek area is at the intersection of a number of lineaments including the Enterprise Valley-Nez Perce, Harvey Creek, and Coyote Creek lineaments. A substantial amount of lacustrine sediment remains in the area and the stepped terraces here are still as much as 2 miles wide. The massive terrace is buttressed by a 1320-foot terrace on the east which currently protects the 1560- to 1640-foot terrace behind, but is exposed to the reservoir on the south where very active slopes exist.

San Poil volcanic rock related to the Enterprise Valley structures and volcanic feeder system are exposed along Nez Perce bay (Section 35, T31N, R36E) and nearby areas (Figure 11). More unconformity slides can be expected here in the future. The lack of bedrock exposures in Sections 25 and 36 (T31N, R36E) indicates that a thick lacustrine section and perhaps a buried bedrock channel may be located here.

A number of 1400-foot terrace remnants occur on the left bank in Sections 5, 8, 17, and 20 (T31N, R37). Their outer edges are marked by nearly continuous recent landslide scarps. At one locality in Section 8 the 1400-foot terrace is very narrow but elsewhere it is 1100 to 2500 feet wide. This terrace is buttressing a 1900-foot ice-contact terrace behind that could present a serious slope problem. The narrow part in Section 8 will be the first area where support for the 1900-foot surface will be removed and larger, more active landslides may begin. Farther north, the buttressing terrace is not present but the slopes seem relatively stable. The ice-contact terraces may have a higher sand-clay ratio than the 1400-foot terrace and may hold higher, steeper slopes better. Exposures in this terrace are poor but seem to be coarse silt or fine sand where it was examined. perhaps clay layers are absent which could account for the apparent stability of this very high terrace.

Inchelium (15-Minute) Quadrangle

Updated topographic base maps for this area include the Inchelium, Wellington Peak, Kentry Ridge, and Rice 7.5 minute quadrangles.

The Columbia River valley extends through the west half of the Inchelium quadrangle. Its direction is roughly north-south but on closer inspection it can be seen to follow long segments oriented north by northeast and north by northwest. The trend is in general parallel to the strike of the Paleozoic age sedimentary rocks exposed in the quadrangle although the possible presence of other structural features submerged beneath the reservoir cannot be ruled out.

A number of cross lineaments occur in the quadrangle but no parallel lineaments or continuation of lineaments away from the reservoir that are in line with Columbia River valley segments were detected. Inspection of lineament maps by Donovan (1983) or using images other than the topographic maps, airphotos, and orthophotoquads used in this study may detect other features or geologic relations not recognized here.

As one moves northward away from the former ice terminus the glacier increased in thickness up to the firn limit which was probably located just south of Hunters during the late Wisconsin ice maximum. The entire quadrangle was covered during the late Wisconsin ice maximum except for a nunatak area to the northeast around Monumental Mountain. Above 5280 feet is an intermediate age soil that marks the upper extent of late Wisconsin ice.

A major extension of ice flowed westward up Hall Creek valley to the Twin Lakes area. An excellent record of decreasing ice levels is recorded by moraines and ice-contact surfaces in the Inchelium and Hall Creek areas. The 1840-foot Hall Creek and 1700-foot Butler Flat surfaces are 2 or more miles back from the reservoir and are not influenced by reservoir processes. The 1640-foot terrace in Section 20 (T32N, R37E) is close to the reservoir edge and will be affected after the narrow 1400-foot terrace at this location is eroded headward.

Lodgment till is common on the east side of the valley above 2000 feet but no major former ice positions are recognizable. Ice flow created numerous whaleback forms on the east side of the valley and the glacier apparently experienced an orderly but rapid retreat.

Ice retreat allowed the Lake Columbia III waters to extend northward and leave significant terrace remnants at the 1520- to 1560-foot level. A major unconformity appears in the lake sediments near Cobbs Creek and suggests that a lowered lake level was followed by the return of a shallower lake. The shallower lake had higher energy currents and the sediments are not as evenly laminated as they are in those associated with the older, deeper lake. These 1520- to 1560-foot remnants produce the major slope problem areas in this quadrangle although Lake Columbia IV and V terrace levels are actively retreating and could also potentially create problems. Much of S.R. 22, the main north-south road on the east side of the reservoir, is built on a narrow Lake Columbia V terrace that is less than 150 feet from the road edge at many locations.

Relatively stable areas in this section of the reservoir are found where alluvial fans and others alluvial slopes grade gently down to the reservoir. Very little or no slope retreat is occurring in Section 10 (T32N, R37E) where a large alluvial fan is located. Bedrock areas are also stable and in some cases a narrow bedrock armor (e.g., Section 9, T33N, R37E) seems to have stabilized the unconsolidated sediment behind. However, unconformity slides can become important at such locations (e.g., Section 25, T34N, R36E).

The island in Section 16 (T32N, R37E) effectively protects the 1320-foot surface immediately to the west from reservoir processes. The stabilizing effects of tree fall on slope retreat are locally shown in this quadrangle. Erosion is greatly slowed in Section 19 (T33N, R37E) where downed trees with their roots still attached to shore greatly slow erosion by breaking up incoming waves.

The widespread 1520- to 1560-foot terrace is buttressed in many locations by the 1320-foot terrace but locally is exposed directly to the reservoir such as in the Inchelium bay area. The large slide in the NW ¼ of Section 6 (T32N, R36E) was threatening houses on the north side of town prior to their relocation in 1985 and 1986. The slump-flow landslide area here may be in transition to an unconformity landslide as bedrock is exposed at its base. A shear zone noted in the bedrock may have been instrumental in concentrating groundwater flow into the failed slope behind. The narrowness of the scar on this heavily vegetated slope shows characteristics more typical of debris avalanche. The wide terrace here buries the old bedrock channel whose exact location is not known but likely extends beneath the town.

The abundance of springs along the terrace edge also contributes to slope instability. Lacustrine sediments overlying relatively impermeable till encourages the lateral movement of groundwater and consequent spring activity. The extent of the till is not accurately known beneath the terrace surface. It extends at least 2.5 miles to the west but was not visible in exposures in the lower bay area. The extent of the underlying till is important in determining areas of slope stability. The Inchelium terrace area coincides with the intersection of the Hall Creek, Stranger Creek, and perhaps another lineament along the Columbia River valley to the east. The Stranger Creek lineament extends completely across the Columbia River to the east side of the valley.

Stabilization of the 1320-foot terrace on the east side of the Inchelium terrace and perhaps a log boom at the mouth of Hall Creek bay may reduce wave erosion on the steep northern slopes.

A summer home in the SW ¼ of Section 21 (T32N, R37E) is built in a precarious position (Figure 25). It is close to the reservoir edge and located on a landslide block that is actively eroding headward.

Another wide terrace area occurs in the Chalk Grade Flat area in the northwest part of the quadrangle. Three major northeast-southwest trending lineaments also occur here. The Pleasant Valley lineament and the lineament following the unnamed valley north of

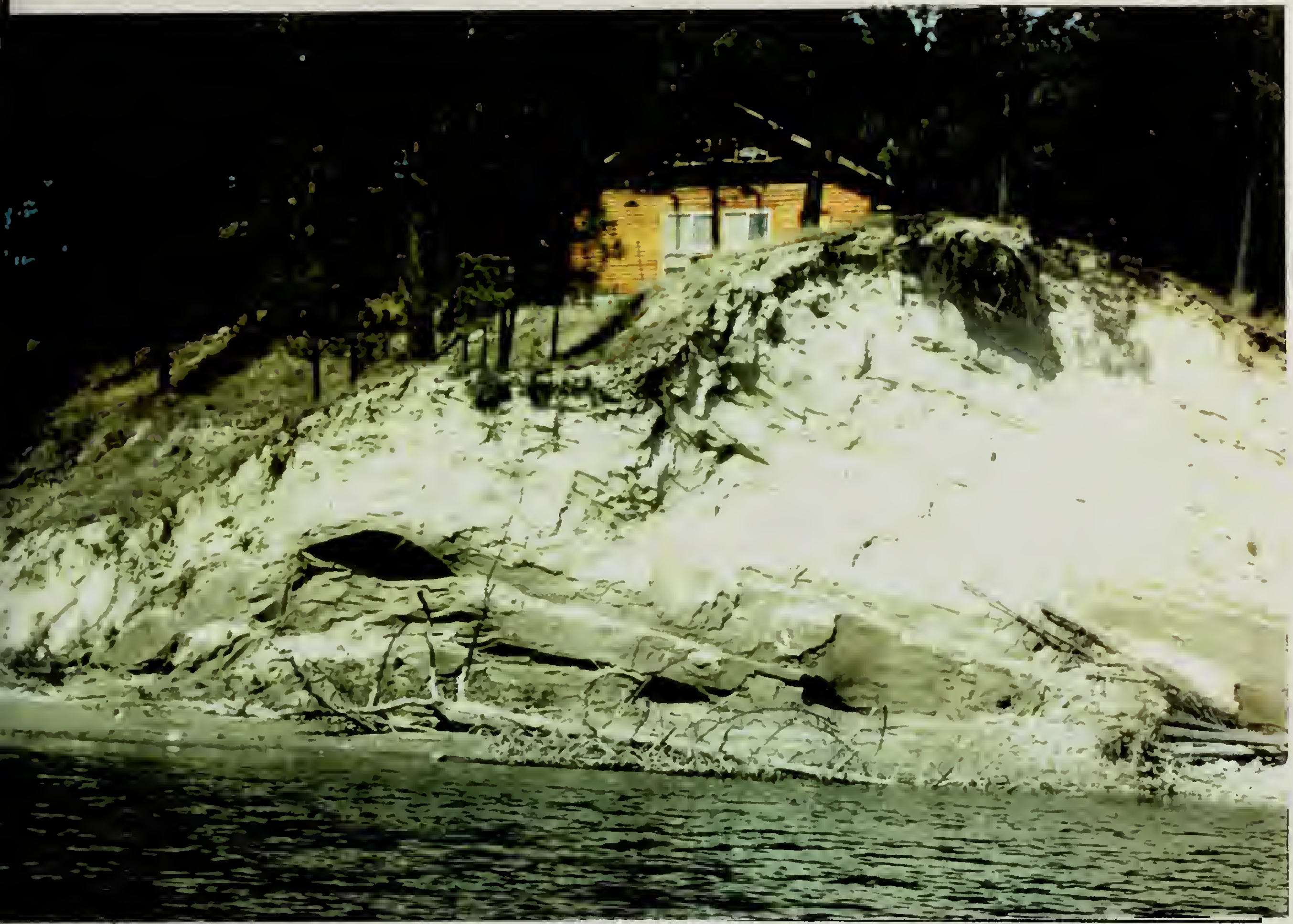


Figure 25 - House on landslide block in Inchelium SW quadrangle. Photo taken on 9/8/83.

Heidegger Hill intersect the terrace. The Chewaka Creek lineament (Rice area) is just south of the terrace and probably played a role in the destruction of the southern extension of the terrace. The 1560-foot terrace in Sections 19 and 20 T34N, R37E) has no buttress and is eroding rapidly. Areas to the north have 1400- to 1440-foot terrace buffers and bedrock armor locally at the reservoir edge. The narrowness of the terrace buffers and the closeness of bedrock to the reservoir edge is a potential problem for road maintenance in many parts of this quadrangle. Both the highways along the west and east sides are relatively close to the reservoir edge in many parts of the Inchelium quadrangles.

Bangs Mountain and Kettle Falls (7.5 Minute) Quadrangles

These two quadrangle are discussed together because the boundary between the Bangs Mountain and Kettle Falls quadrangle cuts directly through the reservoir in the northerly map area. From the south, the Columbia River valley trends to the northeast to the Colville River and Sherman Creek area where the valley trends north by northwest and then north by northeast past the Kettle Falls highway bridge. A large number of lineaments are apparent on airphotos of the Bangs Mountain quadrangle where the bedrock has been effectively scoured by late Wisconsin glaciers. Fewer lineaments were noted in the Kettle Falls quadrangle to the east where slopes are more till covered. Orthophotoquads were not examined nor was a detailed lineament study conducted so other lineaments have no doubt been missed. Some of the prominent lineaments, such as the Sherman Creek, Martin Creek, Hallam Creek, and Blue Gulch are not shown on the geologic map.

The dominant lineament trend is to the northwest although other directions are also represented. The Sherman Creek-Colville River lineament extends across the Columbia River Valley and curves northward.

Late Wisconsin ice covered all areas in these quadrangles and left a record of decreasing ice volumes in the elevation of lateral moraines and ice-contact terraces, especially in the Bangs Mountain quadrangle. A tongue of ice extended from the Columbia River lobe into Sherman Creek where it created a large, temporary lake and a number of ice-contact terraces in the Trout Creek area. The possible catastrophic release of this lake, and/or perhaps others, could be the source of the water that produced some of the south-flowing current indicators in downvalley, flood-like sediments. At one point the ice-dammed lake spilled around the southwest side of Bangs Mountain into the Columbia River valley and cut a narrow, spectacular canyon (Donaldson Draw, elevation 2820 feet) some 600 feet deep.

Ice position evidence in the Kettle Falls quadrangle is more obscure than in the Bangs Mountain Quadrangle although the southeast part of the quadrangle around Mingo Mountain was not investigated carefully because of poor access and time restrictions. Ice flow coming from the Colville Valley may have outlasted that along the Columbia River valley. A moraine-like ridge of till along the Colville River bay indicates that the Columbia River glacier was somewhere to the north of this location when the Colville Glacier was still flowing into the Columbia River valley.

The late Wisconsin ice retreated at least as far as Marcus (5 miles north) and then readvanced to about 1 mile south of the northern boundary of the Kettle Falls quadrangle where ice-drag features are apparent in the lacustrine sediments and complex mixings of till and lacustrine sediments are exposed in the bluffs along the right bank. A temporary ice position is probably marked by the arcuate shape of "Mission Bay" (informal Reclamation name).

In addition to the high ice-contact terraces along Trout Creek (maximum elevation of 3200 feet) and one at 1800 feet along Sherman Creek, Lake Columbia III extensions are also present and represented by the prominent 1560- to 1600-foot elevation deltaic and lacustrine terrace sediments forming much of the massive peninsula west of Kettle Falls. Lower remnants at 1440- to 1480-foot elevation in the Reed Terrace-Roper Creek areas may be isostatically uplifted remnants of the Lake Columbia IV terrace.

Slump-flow landslides are most common in these quadrangles with some unconformity slides and one multiple alcove slide near the mouth of Sherman Creek that occurred in 1951 (Jones and others 1961). High terrace landslides occur in the Reed, Roper Creek, and "Spring Creek" (Reclamation name) terrace on the right bank in the Colville River Bay, Mission Bay, and south of Bradbury Campground on the left bank. An excellent exposure of a Pleistocene age landslide block covered by horizontal lake sands and silts occurs in the Reed Terrace area (NE ¼, Section 34, T36N, R37E).

The Colville River bay is located along an extension of the Sherman Creek lineament which crosses the reservoir from the west bank. Headward retreat by the Colville River has cut a deep canyon and the possibility of a buried channel on the east side of Hawks Nest may contribute to the prominent landslide activity on the south side of the 1560-foot Kettle Falls surface. The area is in at least its second cycle of landslide activity. Two older landslide scarps are present in Section 36 (T36N, R37E). Debris in the west scar needs to be removed before the crown of the slide experiences more major movement. Most of the debris has been removed from the east scar and movement could occur again at any time here.

A Lake Columbia V terrace near the Kettle Falls bridge (NW ¼ Section 14, T36N, R37E) has a number of houses and is actively eroding (Figure 26). Some houses are quite close to the reservoir at present.

On the north end of the Kettle Falls surface along "Mission Bay" the full height of the 1560- to 1600-foot terrace looms above the reservoir. Slope movements and alluvial processes had graded the slope back to a more stable slope angle but shore processes have produced slope steepening and a continuous series of high terrace landslides.

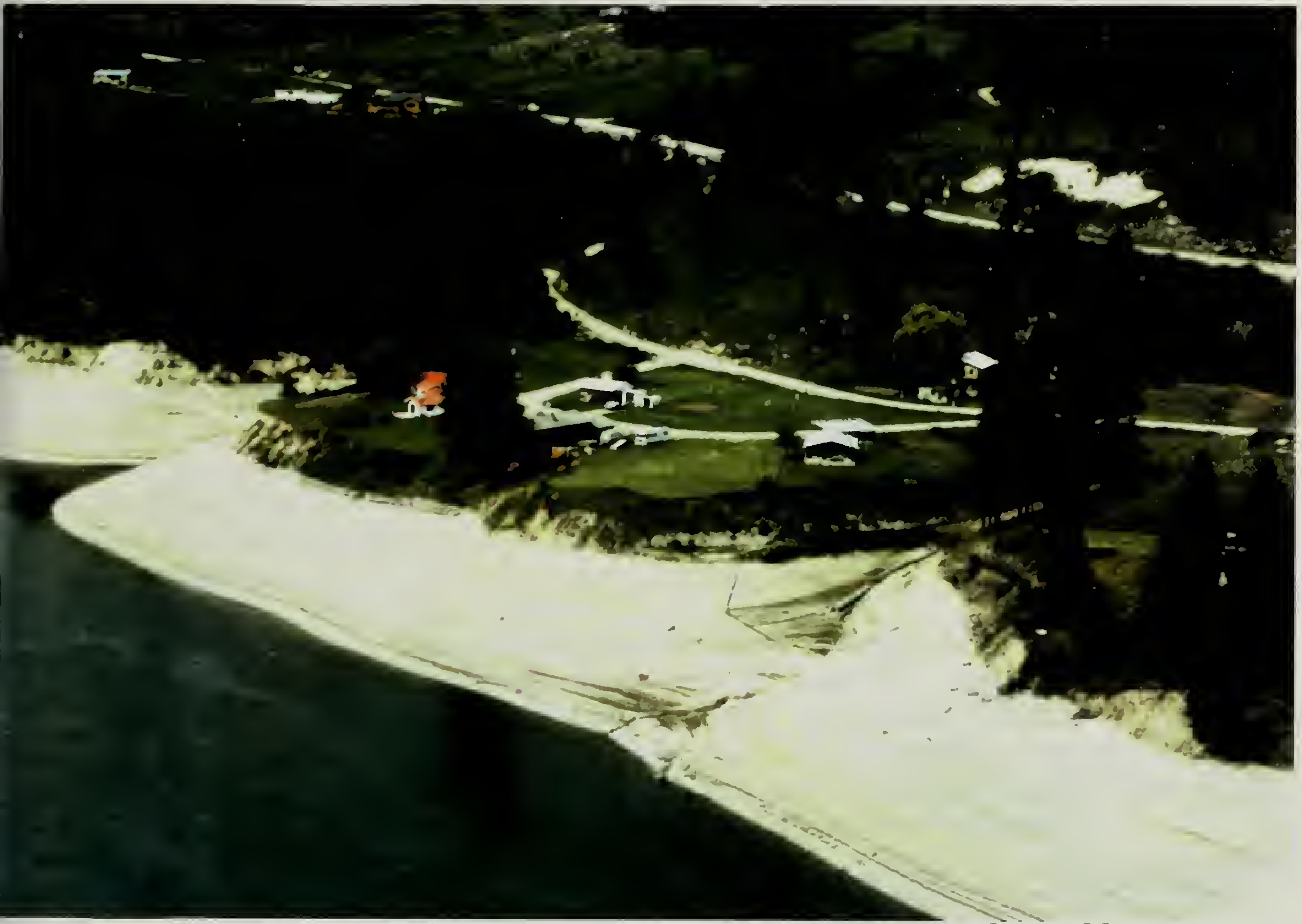


Figure 26 - Right bank terrace south of the Kettle Falls bridge. Note active slopes on low terrace (1360') and landslide in road cut along Rt. 30. Photo taken on 5/25/84.

Lacustrine sediment here is mostly silt but some clay layers exist. Carbonate cement is locally important and may contribute to larger blocks failing during some landslides. Riprap along the highway has slowed shore retreat. Most of the north-facing slope along Mission Bay is unprotected by riprap or other long-lasting armor, and slide activity in this area is very active.

The Columbia River or Colville River may have flowed through this area at one time before Lake Columbia III sediments buried these old channels. Ice in the Colville Valley was fed from glaciers to the north rather than being a major sublobe of the Columbia River glacier as formerly supposed. Outwash and deltaic sediment from the Colville Valley slopes westward and pushed the Columbia River to a more westerly position by the time Lake Columbia lowered and downcutting commenced. Thus, the Columbia River acquired a new course over a bedrock ridge to the west and formed Kettle Falls which is now submerged beneath the reservoir. Blue Gulch is cut into the valley fill material and is on trend with the Colville Valley and the lower end of Sherman Creek across the reservoir. Thus, the Blue Gulch channel may be located along the old buried channel.

The origin of the large, "alcove shaped" Mission Bay may be inherited from a stillstand of the Kettle Falls readvance or, alternatively through landslide retreat and wave erosion. If a buried channel occurs at the head of Mission Bay, the resulting rapid retreat of slopes by landslide processes might account for the broad, shallow bay. The smoothness of the bay profile is more like an ice-contact surface, but the lack of a coarse facies of sediment at Mission Bay could be used to argue against an ice front here.

Marcus and Boyds (7.5 Minute) Quadrangles

The discussion of the Boyds (7.5 minute) quadrangle is included with that of the adjacent Marcus (7.5 minute) quadrangle because only a small part of the reservoir extends north by northeast from the south end of the map into the wide valley section near the confluence with the Kettle River. The extension of the main Columbia Valley is in line with the massive slide in Section 23 (T37N, R37E) that is one of the larger landslides (pre-reservoir) along Lake Roosevelt.

The Kettle River trends slightly west of north and is in line with the Mission Bay area in the Kettle Falls quadrangle. The Columbia River valley makes a sharp bend at the Kettle River confluence and trends east by northeast past the town of Marcus to Section 27 where the valley turns sharply and trends north by northwest. A number of cross lineaments also occur here with northwest and northeast orientations.

The west-east trending Deadman Creek and Pingston Creek-Nancy Creek lineaments connect across the reservoir. The prominent Kamloops Island-China Creek lineament is located along the bedrock wall-valley fill contact in Sections 13 and 23 (T37N, R37E) and extends northeast across the reservoir into China Creek. Orthophotoquads and

other images (besides airphotos) were not examined for these northern quadrangles so that some lineaments and other structural features may not have been detected. Also, many of the obvious lineaments are not shown on the geologic maps.

Late Wisconsin glaciers covered the entire area but prominent ice positions occur at Deadman Creek along the Kettle River and near the town of Marcus along the Columbia River valley. A prominent lateral position is marked by low moraines and kame and kettle topography at the 1800-foot elevation in the Pot Holes (Section 10, T37N, R38E) area. The 1680-foot kame terrace located just north of the Pot Holes also has numerous kettles on its surface and records a slightly lower position of the glacier.

The 1560-foot Lake Columbia III terrace remnants occur in Section 24 (T37N, R37E) and adjacent areas and in Section 5 (T37N, R38E) and 32 (T38N, R37E) along the north part of the Marcus quadrangle. These are the last major remnants of the Lake Columbia III terrace along the Columbia River valley although some smaller remnants of what may be Lake Columbia III deposits occur in the Bossburg and China Bend quadrangles. Lake Columbia IV and V terraces are also present.

The Marcus quadrangle contains the northern extension of the Kettle Falls peninsula area near historic St. Pauls Mission. Lower terraces are cut into the northern tip of the peninsula at 1340 feet and 1480 feet. Some riprap protects part of the northeast edge of the peninsula but large landslide scarps, some 60 feet high, line the terrace edge. The historic Mission is within 600 feet of the reservoir on the northeast side.

A number of potential problem areas occur in the Marcus quadrangle including the position of SR 22 on the edge of the 1640-foot terrace close to the reservoir in the SW ¼ of section 7 (T36N, R38E) and the high terrace landslide in the SW ¼ of Section 16 (T37N, R37E). Many of the landslide problems are associated with the wide valley area near the mouth of the Kettle River where a number of major lineaments intersect. Landslides are further removing valley fill material in "Welty Bay" and the area across from Evans Campground. As terrace recession progresses and the reservoir width enlarges, more fetch will be available and wave action will intensify and rates of slope retreat will increase. Bedrock is beginning to be exposed on the northwest side of Welty Bay but no bedrock is yet exposed in Sections 23 or 26 (T37N, R38E) and surrounding areas suggesting that the entire 1.5-mile wide 1560 feet and nearby 1400 feet and 1340- to 1360-foot terraces may be very vulnerable to continued landslide.

A buried channel or channels may be involved in the promotion of landslides along the Welty Bay terrace. A number of short lineaments and associated valleys empty onto the top of the terrace. No surface streams exist and the direction of groundwater movement is unknown in detail but likely contributes to landslide activity along the terrace edge.

A number of springs emerge on the southwest and south sides of the Welty Bay terrace but some of these may result from the intense irrigation on the 1340-foot terrace. The history of the massive landslide in Section 23 is unknown but the landslide appears to be pre-reservoir but could be very early historic in age. The entire 1560-foot terrace edge along the west side of the Welty Bay terrace has failed and is partially armored with landslide debris. The entire east side is rimmed by landslide scarps. Older scarps in Section 19 (T37N, R38E) are relatively stable now because of the landslide debris that creates the shallow cove and protects the shoreline from intense wave action. The older scar to the north (SW ¼ Section 18) along the 1400-foot terrace has been cleaned out and is now being steepened by shoreline processes. This area is becoming more susceptible to new slide activity.

Areas of relatively stable slopes occur where alluvial fans or alluvial slopes have produced a gently sloping surface that grades down to the reservoir. The areas in the SW ¼ of Section 36 (T38N, R37E), the Snag Cove Campground area (Figure 16), and the NE ¼ of Section 12 (T37N, R37E) are examples.

Low terraces of thick gravel are also relatively stable because of their low height above the reservoir, permeability, skin slide behavior, and gravel armor. Such surfaces occur near the Marcus Island Campground and the Evans Campground area. The large log boom around the mouth of the Kettle River to catch floating debris has given some protection to adjacent unstable slopes (SE ¼ Section 28, T37N, R37E) by reducing wave erosion and, therefore, the frequency of landslides. However, two houses here are located above relatively fresh landslide scars.

Bossburg and China Bend 7.5 Minute Quadrangles

The Columbia River valley trends northeast from the south edge of the Bossburg quadrangle, runs north to about 1-mile south of North Gorge Campground, trends northeast into the China Bend quadrangle to the mouth of Flat Creek where it turns south by southeast to China Bend, then northeast to Section 6, north to Section 25 (T39N, R38E), and then northeast into the Onion Creek quadrangle. Lineament trends are pronounced in both the northwest and northeast directions although mostly the northeast-southwest trends control the Columbia River valley in these quadrangles.

Along the Columbia River and south of the river are a number of north-south trending lineaments such as the Swede Pass, Phalon Lake, and Williams Lake trends. The north-south China Bar segment (China Bar quadrangle) is controlled by the Swede Pass lineament and the North Gorge Campground segment is no doubt controlled by a similar trending feature. Orthophotoquads and other images (other than airphotos) were not available so a detailed lineament study was not done. Many of the lineaments discussed here are not marked on the geologic maps compiled for this study.

Glaciers completely overran the topography in this area. Evidence of deglaciation is present in the 1920-foot kame terraces in the SW ¼ of the Bossburg and N ¼ of the China Bend quadrangles as well as in lower levels at 1760 feet, 1720 feet, and 1600 feet.

Levels below this may be either Lake Columbia or local ice-contact surfaces. Where lacustrine clays are present near the axis of the valley, a Lake Columbia origin is most likely. Ice overran the bedrock divide in the south part of the China Bend quadrangle and created three narrow valleys that were later used as spillover passes by ice marginal streams and lakes (Figure 27). The meltwater flowed south through the Williams Lake, Swede Pass, and Phalon Lake passes into Echo Valley which in turn empties into the Colville Valley.

Till overlying lacustrine clays in the NW ¼ Section 28 (T39N, R39E, China Bend quadrangle) and at other locations reflects a fluctuating ice front or readvance of ice, perhaps related to the Marcus Moraine and Kettle Falls readvance.

Most of the area has unconsolidated sediment showing landslide scarps exposed along the reservoir edge with perhaps 5 percent of the reservoir within the quadrangles being bedrock rimmed. Much of the reservoir edge is buttressed by 1320- to 1360-foot terraces with only a few areas such as the 1560-foot terrace at the mouth of the unnamed canyon in Section 25 (T38N, R37E, Bossburg quadrangle), the 1400-foot terrace near Marble (SE ¼ Section 28, T39N, and R39E), and the 1600-foot surface in Section 28 (T39N, R39E) having high terraces facing the reservoir. Except for the China Bend and the Marble terraces, these high terraces are surprisingly lacking of abundant landslide scars. The amount of clay in the section may be a factor. The presence of riprap along the railroad also helps provide stability for the 1600-foot terrace.

The lower 1320- to 1360-foot terraces apparently have enough Lake Columbia V clays to allow their slopes to fail consistently. Thus, these quadrangles mostly have low terraces and low volume landslides. Slope retreat is progressing and higher terraces will eventually be exposed to reservoir shoreline processes. Depending on clay content and other factors, some of these higher terraces will undoubtedly experience slope failure.

Stable areas include those with riprap (placed near the railroad) such as in Section 22 (T38N, R38E, Bossburg quadrangle, left bank), the 1600-foot terrace in the Marble area, the alluvial fan and alluvium areas (NW ¼ Section 19, T38N, R38E), North Gorge Campground area (Section 10, T38N, R38E, Bossburg quadrangle), and the Ryan Creek area (China Bend quadrangle).

Boundary, Northport, and Onion Creek (7.5 Minute) Quadrangles

The entire area represented by the Boundary, Northport, and Onion Creek quadrangles was subject to glaciation during each glacial advance of the Pleistocene, but only late Pleistocene glacial deposits have been recognized. Thin, discontinuous patches of drift including both till and outwash remain on the adjacent mountain slopes and in the tributary valleys. Along Lake Roosevelt exposures of till are scarce with lacustrine sediments, glacial outwash, and local fluvial deposits comprising the terrace material. Eolian sands commonly cap these terrace units. The Columbia River lobe blocked off

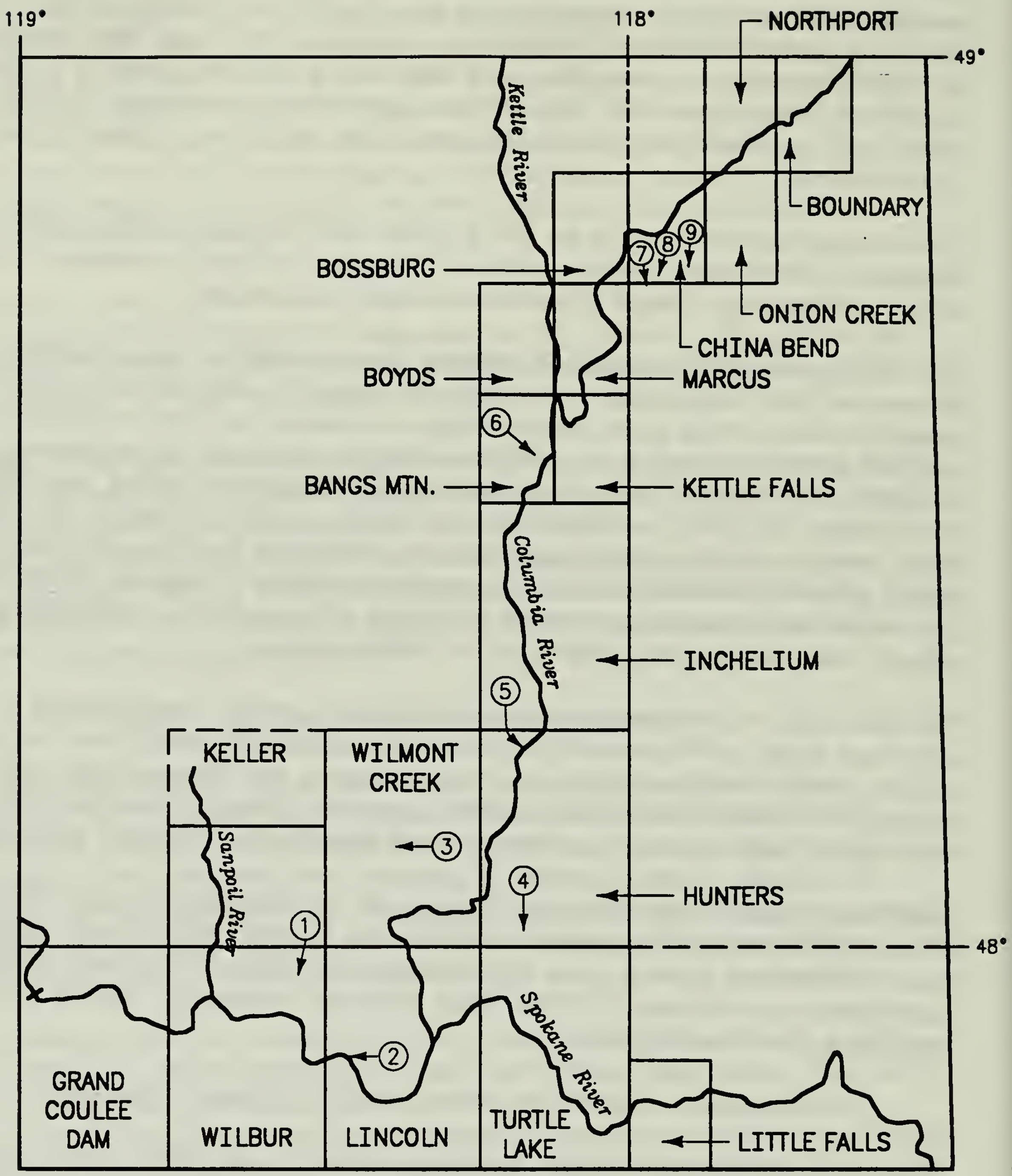


Figure 27 – Major spillover passes. Arrows indicate direction of water flow. 1=Brady Creek–Friedlander Meadows Pass, 2720'; 2=George Ck. Pass, 2400'; 3=Cougar Canyon, 2600'; 4=Newbell Lake, 2240'; 5=Butler Flat, 1800'; 6=Donaldson Draw, 2820'; 7=Williams Lake, 1950'; 8=Swede Pass, 2240'; 9=Phalon Lake, 2600'

several of the tributary valleys providing conditions favorable to the development of kame terraces which are mostly composed of low energy deposits of sands, silts, and locally clays. No recessional nor terminal moraines were recognized, however, two local ice stagnation areas were identified. Coarse sands and gravels associated with a kame and kettle topography indicate ice stagnation. One such area is located on the left bank east of the Boundary Highway near the Canadian boundary. A second ice stagnation area is primarily along the right bank of Big Sheep Creek (Section 23, 24, 25, and 16, T40N, R39E, Northport quadrangle).

The Columbia River traverses the area for about 16 miles. After entering the United States, the river flows south for about 2 miles and then flows in a southwesterly direction for about 14 miles before leaving the area covered by the three maps. Unlike other areas on Lake Roosevelt, turbulent water with eddys and rapids are common in this northern segment. This is most apparent when the water level of Lake Roosevelt has been lowered, thereby increasing the stream gradient. At full pool elevation (1290 feet) Lake Roosevelt ends at Northport. River elevation at the U.S. - Canadian border exceeds 1295 feet.

Between Northport and Deadman's Eddy, Paleozoic metamorphic rocks, mostly slates and argillites, border the river along much of the left bank. Immediately upstream from Northport, the river is confined to narrow channel in limestone and locally split by islands of the same Paleozoic bedrock.

Becker Flat by Deadman's Eddy is the top of a thick valley-fill sequence. The buried Pleistocene valley conducts a significant flow of groundwater into the reservoir and contributes to the massive slope failure behind Deadman's Eddy.

For much of the area traversed by the Columbia River along this upriver reach, the river occupies a wide valley with a narrow alluvial channel. This narrow bedrock channel located immediately north of Northport as well as at the Little Dalles are anomalous conditions. It may be that either glaciofluvial deposits transported out the Big Sheep Creek drainage pushed the Columbia River channel southeast and/or the Columbia River was superimposed from an outwash surface onto the underlying bedrock. The narrow bedrock channel suggests a relatively recent (late Pleistocene?) development.

These areas of bedrock appear to be stable but locally they are capped by overlying terraces which may be subject to mass wasting.

Downstream at the Little Dalles (N ½ Section 22, T39N, R39E, Onion Creek quadrangle), the Columbia River occupies a narrow canyon in early Paleozoic limestone. Whether this rock is particularly resistant to channel widening or whether there has again been a change in the channel because of recent superposition is unclear. Certainly the evidence for superposition here is weaker than that for the channel north of Northport. The area lacks tributary valleys to contribute sediments and the terrace levels are variable. Whatever the cause, the river occupies a narrow bedrock channel and probably lacks a graded profile along this reach.

With the exception of the river segment between 2 and 4 miles south of Northport (Section 3, 9, 10, and 13, T39N, R39E, Northport quadrangle), lineaments do not extend down to Lake Roosevelt. Locally these lineaments provide avenues for runoff from the adjacent mountains onto the lower terraces where both dissection or deposition may take place. Alluvial fans sometimes form where these lineaments join the reservoir. Squaw Creek (Section 3 and 10, T39N, R39E, Northport quadrangle) with the largest tributary drainage system has the potential to contribute debris flows into the reservoir under favorable weather conditions such as during a torrential rain.

The terraces bordering the reservoir generally are between 1320 feet and 1440 feet in elevation. The stratigraphy is conducive to mass wasting, however, large landslides do not appear to have developed because of low relief. These low terraces are best developed along the right bank in association with the Boundary quadrangle and along both banks at Northport. Both Northport and the Lowry Landing Strip are on low terraces. These surfaces are often capped by eolian sands over coarse outwash gravels. Both have high infiltration rates and must contribute water to the groundwater perched on lacustrine silts and clays below. Other water sources include runoff from the adjacent hills and local irrigation.

CONCLUSIONS

General

1. The main object or goal that was accomplished during this intermediate level study of the geology and landslides along Lake Roosevelt was to provide a general base map that shows the types and locations of unconsolidated sediments and other geologic features in the 39, 7.5-minute quadrangles that cover Lake Roosevelt.

2. Most of the unconsolidated sediments in the Lake Roosevelt area are late Wisconsin in age and probably date from 11,000 to 17,000 years ago. Thus, knowledge of the events in this time frame is of maximum use to USBR personnel working with sediment-related problems.

Glaciation

1. The Lake Roosevelt area has been subjected to at least three major episodes of glaciation. The record of older glaciations is best preserved in the Ft. Spokane (Lincoln quadrangle) area although some evidence of older glaciations exists in the San Poil and Enterprise Valley areas as well.

2. Late Wisconsin ice advanced into the Grand Coulee area and nearly to the Columbia-Spokane confluence and into the Spokane Valley via the Enterprise Valley. Major ice still stands or readvances occurred in the Castle Rock area, Kettle Falls, and Marcus areas. A less significant ice front stabilization occurred near the town of Hunters.

3. Late Wisconsin ice advanced to the Brush Creek area in the San Poil River valley where large boulders on and in a steeply-sloping outwash terrace occurs.

4. Because the glaciers here usually terminated in a glacial lake, very little "textbook" lodgment till occurs along the lower elevations near the reservoir. Water-lain tills are much more common and are sometimes difficult to distinguish from outwash sediments.

5. Reworking of glacial till and outwash by catastrophic Lake Missoula floods descending the Spokane River valley has obscured the original history of many sediments.

6. Isostatic adjustment seems minimal in the Lake Roosevelt area, perhaps because of the rapid advance and retreat of late Wisconsin glaciers. Uplift of perhaps 40 feet may have effected the upper Columbia River valley where glaciers were thicker and loaded the crust for a longer interval of time.

Terraces

1. At least four major terraces (approximately 1700 feet, 1560 feet, 1400 feet, and 1360 feet) formed along the Columbia River valley as the base level lowered in response to erosion of the bedrock lip of Grand Coulee and the northward retreat of the Okanogan glacier.

   For a while, glacial Lake Columbia may have become a self-dumping lake sending flood waters into the lower Columbia Valley and allowing higher terraces to be notched before ice advanced and created another lake and a lower terrace. However, very late Wisconsin debris dams must account for lakes persisting int eh Columbia Valley as recently as 11,000 years ago.

2. High stands of the glacial lakes are shown by strandlines as high as 2500 feet in the Grand Coulee 15 minute quadrangle. Strandlines are not preserved in other quadrangles except for the very western part of the Wilbur 15 minute quadrangle. Lake terrace elevations only provide lake bottom elevations.

3. The terrace sediments have contributions from glaciers, glacial lacustrine, glacial fluvial, and glacial flood sources. Fine-grained lacustrine sediments are widespread and can be a serious hazard to slope stability.

4. Graded sand units with ripple lamination and other high current energy features in the terrace sediments are attributed to catastrophic floods entering the more placid waters of the glacial lakes. These rythmites are interbedded with varved lacustrine muds and are very common from Grand Coulee Dam to the Hunters area and up the Spokane River valley.

Catastrophic Floods

1. At least 31 late Wisconsin floods affected the Lake Roosevelt area although Atwater (1984) believes that 89 or more may have occurred. All of these recorded floods need not be from Lake Missoula but some may be more local outburst floods from the Columbia River and San Poil River glaciers.

2. Flood bars from Missoula floods are common in the narrow Spokane River valley where higher energy flood currents and shallower lakes existed. Only a few flood bars occur in the wider, deeper Columbia River valley downstream. Examples of giant current dunes exist in the Little Falls and Lincoln quadrangles.

3. Glacial Lake Columbia itself may have been a reoccurring, self-dumping lake late in Wisconsin time.

Landslides

1. Landslides along Lake Roosevelt can be informally designated as:

    a. Slump-flow landslides.

    b. Multiple-alcove landslides.

    c. Skin slides.

    d. Unconformity landslides.

    e. Nonbasalt bedrock landslides.

    f. Basalt bedrock landslides.

2. The recent flooding by a deep reservoir (Lake Roosevelt) into a relatively narrow and deep Columbia River valley containing large quantities of unconsolidated sediments has triggered a cycle of slope adjustment that will continue for millenia. Many slopes will continue to fail until sediment is removed back to the more stable bedrock surfaces along the valley margins.

3. The most stable slopes appear to be on granite bedrock (basalt) or on alluvial fans or alluvial slopes that incline gently to the reservoir.

4. Basalt bedrock landslides can be very large and destructive. Areas where the basalt-granite contact is at or below reservoir level (Seven Bays-Lincoln area) should be carefully studied. The removal of terrace sediments against basalt cliffs may remove the buttressing effect and contribute to slope failure of the basalt.

5. The 1872 earthquake may have caused some landslides in the Lake Roosevelt area. A similar earthquake today could conceivably cause large slide waves and considerable instances of slope failure.

6. Areas where buried valleys exist may be particularly vulnerable to frequent and large landslides because of the concentration of groundwater flow in these buried channels. The known areas such as Mission Bay (near Kettle Falls), Sherman Creek, Nine Mile Creek, the Colville River, and Hall Creek should be further evaluated. Other potential buried valley areas should also be studied.

7. The effects of cementation of sediments should be further studied. Well-cemented terrace sediments add strength to a slope but may ultimately cause larger landslides when slope failure does occur.

8. Areas across or near to Ft. Spokane campground, as well as other areas along the reservoir, may have a high potential for a large landslide and the generation of large lake waves tens of feet high.

9. Slope retreat rates increase very rapidly at maximum pool elevation.

10. Landslides will increase in frequency and magnitude as lower buttressing terraces and slopes are removed from the front of higher terraces.

11. Older landslide scar areas are more likely to be activated in large volume landslides than are areas with fresh- appearing, recent landslide scars.

12. A landslide in the narrow canyon immediately below Little Falls Dam could impound the Spokane River. Water could back up rapidly and endanger a number of houses and possibly the facilities at Little Falls Dam.

RECOMMENDATIONS

General

1. Large scale maps geologic maps of selected, critical, areas along the shoreline using a 1:4800 scale USBR topographic map base would provide more detail and more useful information for geologists, engineers, and land use planners than the present 1:24,000 scale used in this study. Many of the geologic features had to be generalized, shown larger than they really are in order to be seen, or had to be omitted. Two examples of large scale maps are included with this report -- Reclamation sheets 28 (Redford Canayon) and 53 (Fort Spokane). This scale or larger would best lend itself to future GIS applications.

2. At least one copy of the 1:24,000 scale geologic maps should be transferred by a draftsperson onto an original USGS topographic map and colored for office reference purposes. Geologic contacts are not always distinct from contour lines on blueline or blackline reproductions. Also, the green overlay is lost during reproduction. If this transfer is done, contacts should be transferred onto the new 7.5 minute quadrangles that are now available rather than the enlarged 15 minute quadrangles of 1940 vintage that were used for the Grand Coulee, Wilbur, Lincoln, Turtle Lake, Wilmont Creek, Hunters, and Inchelium areas. New quadrangles reflect current roads, cultural features, names of geographic features, etc.

3. More detailed mapping and compilation of existing geologic data including bedrock should be done.

4. A more thorough lineament study should be completed for the reservoir utilizing all available geologic information (especially structural information), previous lineament studies in and near Lake Roosevelt, and all appropriate remote sensing images. The base maps should be the currently available orthophotoquads and the newest 7.5 quadrangles.

5. A special effort to map below the 1290-foot level should be made during the spring drawdown. A 1:4800 base map will be necessary to map in sufficient detail. Should a major drawdown be necessary at any time in the future, detailed mapping should be given high priority.

6. In addition to slump flow and basalt landslide hazards, other hazards to construction sites and people should be considered including the presence of shear zones in bedrock and hazards from flash flood, debris or mudflows, and large lake waves.

7. Localized areas of high land use such as Seven Bays, NPS campgrounds, the Spokane Tribe casino site near Fort Spokane; the Hall Creek-Inchelium area, and the Kettle Falls-Mission Bay areas should be very carefully studied to determine if any adverse geologic conditions exist that could be threatening to life or property. Areas of less intense use should also be examined for similar hazards or potential problems after the more critical areas have been adequately studied.

Terraces

1. More detailed mapping on the 1:4800 base maps would provide more accurate placement of contacts and more detailed stratigraphic information could be recorded.

2. The Q1z term that designates interbedded lacustrine mud and sand should be better refined. The number of clay units, thicknesses, and percent of clay could be better designated, particularly if the 1:4800 base map were used.

3. Terrace correlation studies using tephrochronology, varve counts, radicarbon dating, and paleomagnetism should be attempted. The number of varves between flood units as well as distinct thicknesses of units might enable reservoir-wide correlations to be made. A varve study also has the advantage of permitting a chronology to be determined and would develop additional stratigraphic information that would have important geologic and engineering applications in slope studies. Such a study should be given the highest priority amongst the possible future studies.

4. Radiocarbon dating of varve layers using an AMS ^{14}C accelerator holds high promise for dating sediments and terraces. A few samples should be submitted to see if this technique give reasonable results in the Lake Roosevelt area.

5. In addition to No. 2 above, sediment texture could be estimated or measured so that the gravel-sand-clay ratio on a 1:4800 scale map can be given more precisely. Thus, the ratio could be given on a separate terrace map as, for example, 30-50-20 to designate the percentage of each size component present in the exposed bluffs.

6. The Hawk Creek-Seven Bays area holds high potential for working out a detailed stratigraphy of late Wisconsin events in glacial Lake Columbia. Comparison with the San Poil stratigraphic section should be attempted to determine whether long distance correlations using stratigraphic, paleomagnetic, and other means is feasible at present.

7. A short investigation of Lake Rufus Woods should be made to determine if sediments there support the proposed sequence of events at Lake Roosevelt. Some volcanic ash layers occur in the lake sediments at Lake Rufus Woods that

would provide some limiting dates since the downstream lake sediments must postdate ice retreat from this segment of the valley.

8. Paleomagnetic studies of lacustrine sediments have a high potential as a correlation tool and should be investigated more thoroughly.

Landslides

1. Better assessment of landslide hazards could be accomplished by the following types of studies:

    a. Map selected reservoir areas using 1:4800 scale maps.

    b. Compile a geologic and historic record of landslide history using old photographs, reports, newspaper articles, records at Ft. Spokane, Ft. Colville, etc., as well as field studies attempting to date specific landslides through geologic means. A map with ages of landslides would provide a useful visual summary of slide activity. Data from the annual landslide inventory could also be summarized for 5- to 10-year intervals. Such a summary would also provide a recent landslide activity index to identify areas presently experiencing greatest slope failure.

    c. Compile information by 7.5 minute quadrangle on length of shoreline with rock, unconsolidated sediment, and active slopes. Graphs and other visual aids could be constructed that would help define problem areas.

    d. Initiate long-term monitoring of shoreline retreat rates in selected areas by actual measurement. Data from the monitoring could be used to determine slope retreat at specific sites so that the influence of reservoir height, type of armor, size and amount of rock armor, etc., can be measured. How long do root anchors last on fallen trees? When logs on the high beach begin to float do they act as battering rams? Do they remain in the same place for months? How does height of terrace or slope affect shoreline retreat?

    e. Study effectiveness of waves and other processes removing debris at base of slopes. How significant are moderate waves? Storm waves? Boatwash waves? What is the frequency of each type of wave?

    f. Study the probability and magnitude of earthquakes that may occur in the Lake Roosevelt area and their anticipated effects on slope stability. What effect have earthquakes had in the past on slope activity? What effect would an earthquake have now? How much liquification of sediments might occur here during an earthquake? How many earthquakes may have occurred in the area in the last 10,000 years?

2. The reservoir should be divided up into terrace units that might share similar geomorphology, geographic location, and physical and groundwater conditions. These units could be given geographic names or river mile numbers and a permanent file developed that includes photostratigraphy analysis of specific sites, historical summary of landslide activity, potentially important geologic conditions influencing the terrace unit, ownership, water wells, observation wells, perhaps land use recommendations, and other information. Having such a file available would allow present technical personnel to add important facts, information, and observations to the file (rather than storing information in one's head) and assure a continuity of knowledge and experience to future employees. New personnel arriving on the Project could use such a file to become acquainted with current and past problems and conditions.

3. The submerged part of the reservoir needs to be studied. The use of airphotos taken at low reservoir levels in conjunction wiht the 1:4800 scale Bureau topographic maps would provide excellent baseline coverage to record the locations of slope failure beneath the lake surface. Whether these slope failures, some of which are large, were reservoir induced or pre-reservoir should be determined. The possibility of "dominoe" landslides could endanger development along the reservoir edge.

4. Separate symbols on the geologic maps should be devised for height of landslide scarps. Perhaps the number or spacing of perpendicular lines on the slide scarp (Figure 2) could be used to designate less than 10 feet, 10 to 40 feet, greater than 40 feet, etc.

5. Old landslide areas should be studied to estimate age of movement. Such a study would help provide estimates of the duration of the landslide cycle. Sag pond sediments would be particularly useful in these studies.

6. Use available airphotos and the yearly inventory to locate houses, trailers, and other structures on the base maps. Standard U.S. Geological Survey maps only show permanent structures -- numerous trailer houses along the reservoir are not shown on maps.

7. A risk evaluation map should be constructed for the entire reservoir that places an ideal boundary far enough back to protect property and life for a reasonable length of time. The basis of the ideal boundary should be drawn on geologic and engineering information rather than on some arbitrary criterion such as elevation

of a fixed number of feet back from the reservoir edge. Buried valley and reservoir-lineament intersections are examples of areas where a boundary line should be placed much further back.

8. More studies at the Seven Bays and Fort Spokane casino site areas should be made to determine what risks may be involved with the present and future development. Some of the information that should be obtained include the location of the basalt-granite contact in the Seven Bays and Lincoln area by using more detailed field studies and perhaps boreholes and geophysical methods. Monitoring wells to determine if additional groundwater is being added by man's activities and knowledge about rates of slope retreat would also be useful for a complete slope evaluation.

9. Evaluate more closely the areas of known and suspected channels that are buried by lacustrine sediments. The areas where rapids and waterfalls formerly existed may have buried channels present and should be evaluated from pre-reservoir data. Some of the areas that should be looked at include China Bend-Flat Creek-Town Creek valley, Kettle Falls surface, Sherman Creek, Hall Creek (Inchelium) area, China Rapids (Hawk Creek area), Hellgate Rapids, and the Little Falls area.

10. Campground areas and areas where houses are presently located should be evaluated for potential hazards. The possibility of large lake waves causing considerable damage should be considered. The large Jackson Springs landslide created a large lake wave. A similar landslide directly across or closer to the Ft. Spokane or other campgrounds or inhabited areas could have serious consequences.

11. Slope stability calculations and risk evaluation should be done for the worst case scenario when the reservoir is at its lowest elevation and groundwater loading of slopes is maximum.

Summary of recommendations for future landslide studies include:

1. Generate large-scale geologic maps of landslides and sediments.

2. Classify each landslide as a particular type (partially completed in this study).

3. Depth, kind, and thickness of sediments should be determined and mapped (partially completed in this study).

4. Designate active and inactive landslides (partially completed in this study).

5. Determine geologic or historic age of each landslide.

6. Investigate submerged portion of the reservoir.

7. Determine rates of movement.

8. Plot location of excavations and bore holes used in study.

9. Divide reservoir into geographic units and analyze each unit as completely as possible given the time and resources available.

10. Develop statistical and graphical techniques of summarizing landslide data for convenience in planning future studies.

APPENDIX A

Glacial Geology

Introduction

Establishing the glacial geology in the Lake Roosevelt area involves answering two basic questions - where was the ice located and when was it there? A careful examination of the sediments and landforms present in the reservoir area enables one to reconstruct the peleography and past depositional environments. A limitation of this method is that only a few, or perhaps no exposures of the sediment may be available to view. Some key sediments may have been eroded away or may be covered by vegetation or Lake Roosevelt. This section of the report describes some of the types of deposits and features that were helpful to determine glacier locations. As will be noted, the presence of a long-lasting glacial lake in the Columbia-Spokane Valleys had a profound effect on the sediments and landforms.

End moraines are the most desirable features to work with because they delineate the former edge of a glacier. Of particular importance are terminal moraines, which are end moraines that mark the maximum extent of a glacier advance. End moraines form where a land-based glacier remains in equilibrium for a sufficient length of time to build a ridge of debris. Where glaciers terminate into a deep glacier lake as was the case in the Columbia Valley, other landforms but no obvious end moraines form.

Till is a relatively unsorted, non-bedded sediment deposited directly by ice. Till may occur as a "smear" over bedrock or it may form massive deposits such as end moraines. Traditionally, it is regarded as originating from direct deposition from the base of the glacier (lodgment till) or form the downwasting of a glacier where meltwater plays a more important role (ablation till).

However, where deep water is present, such as at the snout of a glacier calving into a glacial lake, sorting can occur and a water-lain till or flow till (Dreimanis 1978) will form (Figures 28 and 29). These latter types of partly-sorted and crudely-stratified tills are much more abundant along the reservoir and for several hundred feet above reservoir level than are the more classic lodgment tills. The distinction is significant because of the textural differences between the water-lain and more conventional tills. Both types of tills usually have an open framework, (large clasts do not touch each other) but the lodgment till has a clay and silt matrix and acts as an aquiclude. Ablation and other water-worked tills have much of the fine matrix removed leaving a more sandy, gravelly sediment whose engineering characteristics are similar to outwash. The few areas where lodgment tills are present immediately next to the reservoir usually show water perching and landslide activity. Lodgement tills occur mostly in the Hunters area and northward where it was thicker and closer to the equilibrium limit ("snowline").

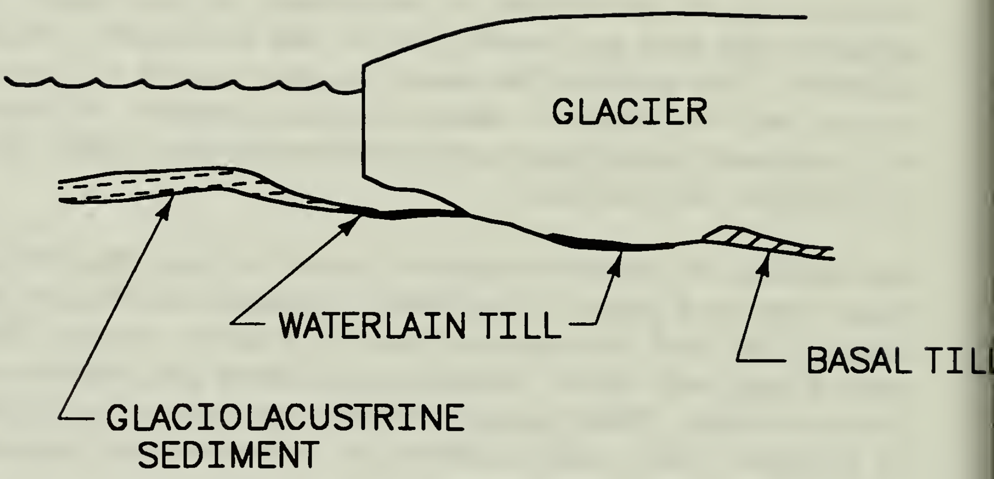


Figure 28 – Waterlain till deposition model (After Dreimanis, 1978)

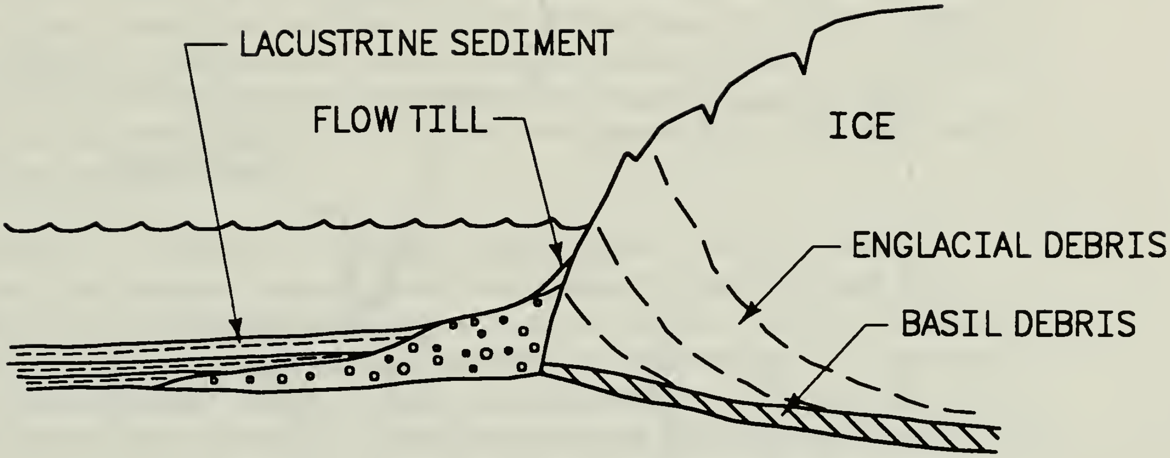


Figure 29 – Flow till depositional model (After Dreimanis, 1978)

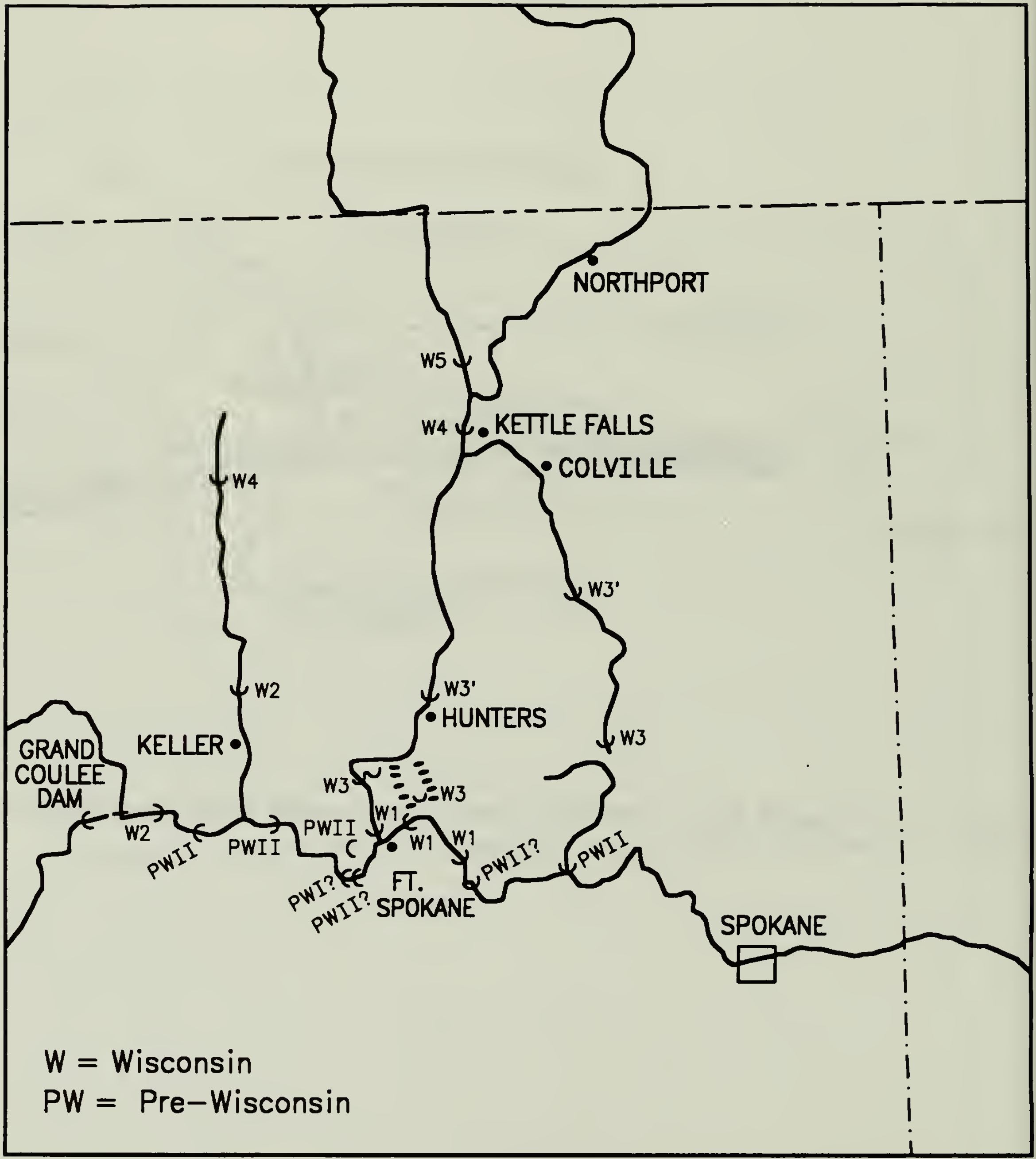


Figure 30 – Ice extent in northeastern Washington.

Increased sorting and bedding occurs in kame deltas and kame terraces where fluvial and lacustrine currents are important. A significant accumulation of this type of deposit requires a relatively stationary ice front and, therefore, indicates an important stillstand or readvance of an ice front. Four major areas of kame delta formation are recognized and are shown along the upper Columbia River Valley as the W3, W4, and W5 ice positions (Figure 30).

Higher in the valley, away from the influence of glacial Lake Columbia, lodgment till is much more abundant. Ablation and lodgment till concentrations, due to equilibrium ice flow conditions, form lateral moraines that mark the former edge of a glacier. Rounded rocks, some of which are foreign to the local bedrock, represent ablation till or fluvially-deposited debris from the wasting glacier (outwash) and are found high on divides overridden by ice. The boundary between rounded and nonrounded rocks often occurs along a former ice margin.

Valley train deposits, so common in glaciated mountain areas, were only locally developed in the Lake Roosevelt area because Lake Columbia persisted until the Columbia glacier had retreated well north of the Canadian border. As Lake Columbia was eliminated or lowered, fluvial conditions returned. Because glaciers still persisted in Canada, these fluvial deposits could be considered distal outwash. Bedded sand and gravel deposits derived from ablating ice form kame terraces along the glacier edge and kame deltas where the fluvial slopes are graded to Lake Columbia at the ice margin.

Kame terraces are built along the lateral margin of a glacier between the glacier and valley wall and often on top of ice after a slight recession of the glacier. In the latter case, melting of buried ice often produces kettle holes. More commonly, ice recession produced local, flat-topped (no kettles), gravely surfaces whose base level was the edge of the downwasting ice. Often, a series of progressively lowered levels of the ablating glacier produced a series of surfaces in a "stepped" arrangement at the margin of the valley. Where tributary valleys joined the trunk glacier, kame lake sediments (e.g., Nine Mile Creek flat at about 1900 feet, 579 m elevation) often substantially filled those valleys and provide an estimate of minimum glacier elevation.

Ice-marginal streams allowed water to cross divides and form spillover channels, some of which are quite impressive. Major spillover channels and their elevations are shown in Figure 27. The elevations in these spillover passes provide a minimum elevation of the ice surface at particular times during deglaciation.

Some of the more spectacular spillover passes include: (1) Cougar Canyon (elevation 2600 feet, 793 m) where meltwater flowed from the Columbia Valley into Wilmont Creek; (2) Donaldson Draw (elevation 2820, 860 m) which allowed meltwater impounded by the Columbia lobe in Sherman Creek (Bangs Mountain quadrangle) to spill over a low shoulder of Bangs Mountain and into the Columbia Valley; and (3) Swede Pass (elevation 2240 feet, 683 m), Phalon Lake (elevation 2760 feet, 841 m), and

Williams Lake (elevation 1960 feet, 598 m) passes (China Bend quadrangle) that permitted Columbia Valley meltwater to spill into the Echo Valley and eventually into the Colville Valley to the south (Figure 27).

The presence of other glacial landforms such as striated bedrock and elongated forms are useful in recognizing that glaciation has affected an area. Striated bedrock is most abundant north of Fruitland (Hunters 15 minute quadrangle) in areas covered by late Wisconsin glaciers. Sediments overlying these polished and striated surfaces are particularly susceptible to mass movement because of the reduced coefficient of friction.

Whaleback forms are best developed near the town of Hunters and northward where the ice was thickest, flowed the fastest, and was, therefore, more erosive. Ice was a less effective erosional agent away from the valley axis and closer to drainage divides. An area of whalebacks in the Lincoln NW (7.5 minute) quadrangle across from Ft. Spokane occurs outside of the late Wisconsin ice margin and must, therefore, be pre-late Wisconsin in age. Similar elongated bedrock features occur at the mouth of the Enterprise Valley (Turtle Lake 15 minute quadrangle).

Tributary valleys clearly showing the typical parabolic shape produced by glaciation occur only in the area covered by late Wisconsin ice. The southernmost of these valleys contains Fall and Coyote Creeks (Wilmont Creek 15 minute quadrangle).

Tributary valleys clearly showing the typical parabolic shape produced by glaciation occur only in the area covered by late Wisconsin ice. The southernmost of these valleys contains Fall and Coyote Creeks (Wilmont Creek 15 minute quadrangle). Valleys to the south, such as Wilmont Creek and Nine Mile Creek, contain thick sediments that may obscure a glacial shape developed during pre-late Wisconsin time.

Cirque-like areas occur at the heads of these tributary valleys, but the lack of local end or cirque moraines indicates that if alpine glaciers were present they must have preceded the arrival of the Columbia Valley lobe. The Cordilleran ice overwhelmed and buried these valleys and for a time impounded a small lake just east of the Cougar Canyon spillover channel (elevation 2600 feet, 790 m). Meltwater spilled over the divide and flowed into the Wilmont Creek drainage. Whether the total 600-foot (180 m) depth of Cougar Canyon was cut during late Wisconsin time or whether some of it was cut during older glaciations in unknown.

Previous Work

I. C. Russell and others in the late 1800's noted some of the effects of glaciation in the Grand Coulee and eastern Washington areas. Elliot Blackwelder and George H. Garrey, students of R. D. Salisbury, noted some of the ice margins in the Grand Coulee and Columbia Valley areas. They traced the late Wisconsin moraine across the Waterville Plateau, north of Grand Coulee, down the Columbia Valley from near Kettle Falls to its inferred terminus 7 miles (11 km) southwest of Fruitland and across the divide into the Colville Valley to the east (Salisbury 1901). They apparently missed the San Poil terminus and mistakenly placed the ice edge too close to Kettle Falls but most of their approximate boundaries appear more accurate than some of those proposed by later workers. This description of their proposed boundaries is based on the verbal descriptions published in Salisbury's (1901) article and Garrey's (1902) Masters thesis. Early geologic investigations by Pardee (1918) noted the presence of glacial features in and near the present site of Lake Roosevelt although the main thrust of his studies was bedrock geology and mining. Pardee (1918, p.52) noted that the Columbia Valley ice had terminated a few miles below the Spokane River confluence and that the San Poil lobe extended as far as Iron Creek and perhaps as far as the Keller area in an earlier glaciation.

Bretz's (1923, 1928, and 1956) classic work on the Channeled Scablands recognized the unique Pleistocene history of the area, namely, that incredibly large floods were unleashed in the eastern Washington area by the catastrophic failure of an ice dam in northern Idaho. Along with these studies he also published several versions of a drift border map of eastern Washington. Unfortunately, his northern map boundary, which is located approximately at 47° 51' N latitude is just south of most of the reservoir.

Bretz (1923, p. 581) recognized at least three episodes of glaciation in eastern Washington; a very old glaciation whose details are very poorly recorded; a younger pre-Wisconsin glaciation (Spokane glaciation) whose effects on the topography are subdued but still visible; and a Wisconsin glaciation that shows strong, distinct effects on the landscape. The older glaciations were best recorded east of the Columbia River near Spokane and only Wisconsin age ice effects were noted in the Grand Coulee area.

Flint's classic papers (1935, 1936, 1937, and 1939) on the eastern Washington area are the most detailed studies available except for the present one. Beginning in the southern Okanogan area (Flint 1935) downstream from Lake Roosevelt and working eastward to Grand Coulee and eventually to the Spokane area, (Flint 1936 and 1937) he compiled a drift margin map for the late Wisconsin that is now regraded as useful although inaccurate. In 1939 Flint described and interpreted the glacial strata exposed during the excavations for Grand Coulee Dam.

Flint did not believe the catastrophic flood hypothesis championed by Bretz and never reinterpreted his work in light of these new ideas even after they become generally accepted by the scientific community in the 1960's. Thus, some of the coarse gravel deposits interpreted by Flint as till are of flood origin. Ironically, the drift border proposed by Flint is at least in part based on flood deposits and, therefore, regarded as much too extensive by all subsequent workers except Bretz, the father of the catastrophic flood idea.

Richmond and others' (1965) and Richmond's (1986) summary of glacial and flood events in Washington, Idaho, and Montana are important regional synopses. The large area covered in the paper and the reconnaisance nature of their study prevented detailed discussions of evidence. For example, the Columbia River lobe is discussed in one paragraph and the San Poil lobe receives a one sentence treatment in the 1965 paper. Yet one major late Wisconsin recessional position in the Columbia River Valley is nearly identical to that proposed in this report. One of the authors of the 1965 paper, Ronald Fryxell, is responsible for much of the interpretation in the Lake Roosevelt area. Unfortunately, no detailed published description of his evidence or work is available and whatever detailed information he had was lost with his untimely death in the 1970's. Richmond's 1986 paper is more accurate for the Columbia River Valley and is based on a 2-day field trip we conducted for him.

Millikan (1981) did a detailed study of the Peter Dan Creek area just northeast of Grand Coulee Dam while employed by the USBR and recognized an older glaciation and two late Wisconsin glacial positions. His work substantiates some of the glacial model conclusions reached by Richmond and others (1965). Millikan's work did not address the more recent recessional history because of the geographic limitations of his study area. However, the detailed study approach employed represents the level of study needed to adequately understand the glacial geology of the Columbia River valley and the entire northeastern Washington area.

Atwater (1984; 1986) did a detailed study of some of the sediments in the San Poil valley. Atwater and Rinehart (1984) placed the San Poil ice margin near the same location as Pardee (1918) and Richmond and others (1965). Their study of the Colville Indian Reservation summarized and modified bedrock information for the Reservation but did not significantly change the ice margin boundary presented by Richmond and others (1965).

Waitt and Thorsen (1984) presented a summary of late Wisconsin glaciation and flood events in Washington, Idaho, and Montana. The article updates much information since the Richmond and others' (1965) article. Waitt and Thorsen (1984) present an improved interpretation of ice margins for areas in Washington east of Lake Roosevelt but the position of the Columbia River lobe is not based on detailed field evidence. Thus, the older Richmond and others' (1965) report shows ice margins more accurately for the Columbia River lobe but Waitt and Thorsens's discussion of absolute ages is more accurate. Richmond's 1986 article presents the best published summary presently available.

Building on the glacial history developed for areas to the east (Kiver and Stradling 1982), this report extends this work westward to the Columbia Valley with the detailed studies from 1982 to 1985. The broad, but incomplete outline of this detailed study and a brief description of field evidence was presented in abstracts (Stradling and Kiver 1984, Kiver and Stradling 1985; 1986). In this report, more detailed evidence for the position of Wisconsin and older ice positions is presented. Also, upvalley ice positions and the recessional and readvance history of the Cordilleran glacier is also presented and integrated into the larger picture of Pleistocene events of the region.

The timing of glacial and climatic events for western North America is constantly being revised as more evidence is discovered. A general synchroneity of events from different regions exists but local differences in ice maximas and fluctuations are probably the rule rather than the exception. In addition, the locations of stillstands of ice during recession may in some cases be due to changes in valley dimensions rather than climatic causes. A tentative correlation chart for the Columbia Valley and nearby regions is shown in Figure 5, (page 17).

Glacial Chronology and Stratigraphy

The relative age of a landform and its associated sediments can be determined by noting the degree of preservation of the original landform, the amount of weathering of the bedrock or sediment, and the degree of soil development. Absolute age can be determined only by establishing the stratigraphic relation of the landform or sediment to datable volcanic ash or organic matter. Unfortunately, no datable organic material was discovered in the Lake Roosevelt area during this study although a few previous radiocarbon dates in or close to the area provide some limiting dates. Although Mazama ash form the Crater Lake eruption (6800 years B.P.) is widespread in the area, samples of older ashes are not abundant. The characteristics of sediments and landforms were extremely useful in determining the relative age and are described in the following sections.

Pre-Wisconsin Glaciation

Scattered exposures judged to represent pre-Wisconsin glaciation consist of weathered till and other deposits lacking topographic expression and displaying a thick, argillic soil. These deposits occur mostly outside of the late Wisconsin ice margin (Figure 30). However, a few patches of older till and deeply-weathered bedrock occur upvalley and survived overriding by late Wisconsin ice. Only the very oldest deposits are discussed in this section. However, some of the intermediate deposits discussed in the next section may also be pre-Wisconsin in age. The variability of characteristics in these deposits is great enough that more than one age is probably recorded.

The most distinctive aspect of the pre-Wisconsin deposits discussed here is the thick (greater than 30 inches), oxidized, argillic soils. The B-horizon color is typically a reddish brown (5YR 4/4) to dark reddish brown (5YR 3/4) and many rock clasts are highly weathered. Granite clasts are often merely "ghosts" or can be broken apart by hand. Soil structures are well developed and clay skins are abundant. Gently sloping bedrock surfaces exposed at least since pre-Wisconsin time are highly argillized or grussified often forming a deep regolith. Varying amounts of loess often cover these surfaces. Steep slopes, particularly those with southerly exposures, are subject to effective erosion leaving a thin or discontinuous regolith making correlations from one area to another difficult.

Exposures of pre-Wisconsin surfaces are located south of the late Wisconsin ice margin and on older nunatak surfaces such as the one at Miller Mountain. The Miller Mountain pre-Wisconsin till occurs on the south flank (Lincoln 15 minute quadrangle) between 2480-foot (760 m) and 2760-foot (840 m) elevation. A thick, argillic soil at the top of Miller Mountain (Wilmont Creek Quadrangle) may even date from Pliocene time (Ula Moody, oral communication 1984). Patches of till in Bockemuehl Canyon, the mouth of Hawk Creek, and the Spokane Reservation surface along S.R. 22 help delineate the former ice extent. The actual limit of pre-Wisconsin ice is imprecisely known because of the scarcity of exposure.

Intermediate Glaciation

The number of known intermediate age sediments and surfaces exceeds those of pre-Wisconsin age in the Lake Roosevelt area. Characteristics of these deposits and weathering features are between those found on deposits of late Wisconsin and pre-Wisconsin ages, thus they are referred to as intermediate age. Richmond and others (1965) considered these sediments to be of early Wisconsin age (30,000 to 70,000 years B.P.). Some support for an early Wisconsin advance does exist in the Great Lakes and the McCall, Idaho, area (Colman and Pierce 1981) but Pierce and others (1976), Porter (1976 and 1979), and Scott and others (1982) consider many deposits with intermediate characteristics to be pre-Wisconsin (130,000 to 150,000 years old). Moody (oral communication, 1984) believes that these intermediate deposits may be middle Wisconsin in age. Because we have no strong evidence supporting either an early Wisconsin, middle Wisconsin, or pre-Wisconsin age, we will refer to these sediments as intermediate or pre-late Wisconsin in age.

Deposits of intermediate age often occur on gently rolling, subdued moraines. These deposits are characterized by depressions which have been mostly filled in with sediments or are completely eroded away, sparse surface rocks, a thinner loess cover than pre-Wisconsin surfaces, and less weathering compared to pre-Wisconsin sediments. Soils are less oxidized and often have a very weak argillic B-horizon with a yellowish brown (10YR 5/6) to a dark yellowish brown color (10YR 4/6). The B zone is weakly to moderately indurated and some clay skins occur on the soil peds. The variability of characteristics, as is also seen in the pre-Wisconsin deposits, is great enough that more than one glacier advance may be represented.

The Spokane and lower Columbia Valleys contain local concentrations of large boulders. These poorly-sorted, non-bedded to poorly-bedded sediments are believed to be end moraines that have been severely reworked by the high energy currents generated by Jokulhlaups (glacier-generated floods) from glacial Lake Missoula in northern Idaho and northwestern Montana. The bouldery Sand Flat sediments (Turtle Lake quadrangle) display large-scale, downvalley-dipping foreset beds that are characteristic of catastrophic flood deposits. Catastrophic floods are unable to carry large clasts great distances when a deep glacial lake is present but can rework coarse debris already present. The positions of ice margins along the lower reservoir and Spokane Valley (including the W1 position just north of the Columbia-Spokane confluence) were placed at these boulder concentrates. Flint and Irwin (1939) also used boulder concentrations as well as other evidence to delineate the margin of the Okanogan lobe upstream from the present site of Grand Coulee Dam and the San Poil lobe on the left bank of the Columbia Valley at Keller Ferry. They also report a till exposure along a roadcut now beneath the waters of Lake Roosevelt near the Keller Ferry.

Evidence supporting the hypothesis that these boulder concentrates are former end moraine positions include:

1. They occur only along the main floodpath in the Spokane Valley and lower reservoir. End moraines containing similar large boulders in the upper Columbia and Enterprise Valleys, away from the full force of the catastrophic floods, still show good moraine topography.

2. Large boulder concentrates occur to the east in the Sand Flat area as would be expected if they were deposited by east-flowing glaciers from the Enterprise Valley. The boulders terminate abruptly on the east edge of Sand Flat indicating that their source was from the west.

3. If the large boulders were entirely derived from floods, then similar debris should be more widespread along the entire valley rather than being concentrated in groups as they are now. There does not seem to be any hydrological reason for these boulder concentrations.

4. Boulder concentrates are in reasonable end moraine locations based on what is known about the distribution and elevation of till and other glacial features.

5. Most of the clasts are rounded and many are not of local origin, thus implying considerable transport. Much of the debris is too large to be fluvially transported; the matrix is too coarse to be of mudflow origin and no evidence of landsliding or local sources of potential slide debris of the right composition could be found.

6. Well-developed glacial stones ("bullet rocks") are present in these deposits (a few with striations).

7. Typically, the initial advance of a glacier incorporates the large boulders freed by interglacial weathering and erosion as well as older debris left by previous glaciations. Thus, where large numbers of boulders 3 feet (1 m) or more in diameter occur, they are not only likely to be glacially deposited, but they are also very likely to represent former terminal moraines. The concentrations of boulders shown as PW II in Figure 30 probably represent intermediate or older ice margins.

A subdued moraine which occurs at 2500 feet (760 m) elevation (SW ¼ NE ¼ Section 33, T29N, R36E) just east of what this report is calling the "Spokane Reservation Surface" (Lincoln quadrangle) marks the former lateral edge of the Intermediate age glacier. Older reddish brown, clay-rich soils with no traces of rounded or foreign rocks occur above this moraine. Thus, the Intermediate age glaciers were as high or higher than pre-Wisconsin glaciers.

Ice near the Spokane-Columbia confluence split, with the main tongue advancing down the main channel and a lesser ice tongue flowing westward into George Creek valley and terminating in the W ½ Section 33, T26N, R35E at an elevation of about 2360 feet (720 m). The massive terminal moraine here is located near the upper elevation of catastrophic floodwaters and away from its main flow, thus the moraine was protected from rapid erosion. The thick soils at this location have a dark yellowish brown B zone (10YR 5/6) and a thick loess cover.

In the main channel of the Columbia, occasional striated rocks and large boulders can be traced to the Hawk Creek area where an Intermediate age glacier may have terminated. An excellent exposure of Intermediate age till overlain by successive loess units displaying late Wisconsin and Holocene soils is exposed in "Reinbold Canyon". This site is located at elevation 2200 feet (670 m) along the farm road in the SW ¼ NE ¼ Section 5, T27N, R36E. The site was apparently partially protected from catastrophic flooding and indicates that the Intermediate age glaciers flowed across the mouth of the Spokane Valley (probably creating a glacial lake) and must have terminated somewhere downvalley. Other sites such as that on Monumental Mountain in the Inchelium quadrangle help establish the upper position of Intermediate age ice.

A diamicton along the Silver Creek Road on the left wall of the San Poil Valley (elevation 1600 feet, 488 m) in the SE ¼ Section 33, T30N, R33E) is believed to be a pre-late Wisconsin water-lain till. The deposit has an open framework with rounded clasts of granite and volcanic rocks surrounded by a sandy matrix. No striated clasts were discovered in the diamicton nor any glacial pavement on the underlying Tertiary age volcanic bedrock. Such features are not surprising for water-lain till. This site lies 4.5 miles (7.2 m) south of a kame terrace deposited near the late Wisconsin ice margin and upstream from boulder and cobble concentrations in the Columbia Valley believed to be former Intermediate age terminal moraines. Bedrock exposures tend to be highly grussified and deeply weathered in the area south of the suspected late Wisconsin ice margin. Deep regolith exposures include those in Meadow Creek and Jack Creek valleys as well as those along the road across from Keller in the NW ¼ Section 28.

Late Wisconsin Glaciation

Modern assessments of a detailed late Wisconsin chronology began with the summary of work for the Northern Rocky Mountains presented by Richmond and others (1965). They proposed that the late Wisconsin (Pinedale) Glaciation began about 25,000 years ago and retreated across the international boundary about 8000 years ago. They also recognized three stages (climatically-controlled readvances without complete disappearance of glaciers during recession) of glaciation in the Pend Oreille River valley and other areas to the east. Two stages of late Wisconsin glaciation were recognized in the Columbia River valley just upstream from the Spokane-Columbia confluence but upvalley moraines, kame terraces, meltwater channels, and other glacial features were apparently not studied.

Based on radiocarbon dates in British Columbia, Clague and others (1980) concluded that much of British Columbia was ice free until after 19,000 to 20,000 years ago. Radiocarbon dates of 17,240±330 and 17,440±330 years B.P. from wood samples in a poorly-sorted gravel deposit (kame terrace) at the Waneta Dam site along the Columbia River just north of the Canadian border are interpreted by Clague and others (1980) as being deposited prior to the late Wisconsin ice maximum. However, the equivalent(?) kame terrace materials nearby in the Boundary quadrangle have abundant, distinct kettle holes and must be very late Wisconsin in age. Thus, this data must either be inaccurate or it must come from an older in situ buried patch of glacial gravel that was preserved in spite of later ice over-ride as Clague and other (1980) suggest or it must be eroded from older material and incorporated into later sediments.

Richmond (1984 and 1986 oral communications) suggests that the organic material may have been incorporated during one of the late Wisconsin interstades. According to this hypothesis, late Wisconsin ice may have advanced well south of the international boundary perhaps 20,000 to 22,000 years B.P., retreated back into Canada, and readvanced back over the international boundary incorporating the 17,500 year B.P. wood into a water-lain till. This hypothesis is consistent with, but not proven by, Millikan's radiocarbon date of 23,898±1040 years B.P. from material in the 1700-foot elevation terrace just downstream from Grand Coulee Dam. This date indicates that the Okanogan lobe covered the present site of Grand Coulee sometime after 23,900 years B.P.

The additional time (3,000 to 5,000 years) provided by the Richmond hypothesis would help to account for the slight but noticeable weathering differences of older late Wisconsin glacial drift to the south and the younger late Wisconsin drift to the north. It also lessens the requirement of very rapid rates of glacial advance and retreat required by the Clague and others (1980) hypothesis. An advantage to the Clague hypothesis is that the shorter period of ice loading would produce less elevation changes due to isostatic adjustments and make certain terrace elevations in the upper Columbia easier to explain. Also, the large McCoy Lake depression (discussed in the "Castle Rock" advance section) adjacent to the Spokane Valley (Turtle Lake 15 minute quadrangle) requires that buried ice persist while major floods occur so that flood sediments do not fill the depression in. The shorter the length of time between ice burial and the last of the major floods the better chance of preserving a large mass of ice. Our interpretation of events in the Columbia Valley makes the late Wisconsin glacial maximum older than the 1700-foot (520 m) lake terrace (glacial Lake Columbia II) which contains the 13, 000 year B.P. Mt. St. Helens ash. This date is more compatible with the Clague and others (1980) hypothesis.

Waitt and Thorsen (1984) also accept Clague and others (1980) interpretation for the Northern Rocky Mountain glacial chronology and also their interpretation that the Puget Lowland and Cordilleran late Wisconsin ice sheets were broadly synchronous. The glacial climax in Puget Sound occurred shortly after 15,000 years B.P. and would be expected to be about the same in the Columbia Valley.

Characteristics of Late Wisconsin Deposits

Late Wisconsin moraines retain much of their original topography. Depressions are deep and steep-sided, ridge crests are sharp and distinct, and surface boulders and cobbles are only slightly weathered, very abundant, and only partially buried by loess.

Lacustrine deposits in the Lake Roosevelt area are almost entirely of late Wisconsin age. Those located in the lower part of the valley were more vulnerable to erosion as base level progressively lowered and the Columbia River adjusted its channel downward. Thus, most of the lacustrine debris has been removed although a significant quantity still remains along the reservoir edge where it creates a major geologic hazard.

End moraines are absent from the lower parts of valleys because of the presence of glacial lakes throughout most of late Wisconsin time. Lateral and a few terminal moraines occur in locations hundreds to a thousand feet or more above reservoir level. Two exceptions are boulder concentrations and low boulder ridges at and below reservoir level near the Spokane-Columbia confluence shown by "W1" (earliest Wisconsin) symbols on Figure 30.

Late Wisconsin soils are generally thin (less than 12 inches) with a poor to very poorly developed textural B zone except where a clayey parent material is present. Oxidation is not very intense and often the B zone is a dark brown color (10YR 3/3). As mentioned previously, soils are slightly better developed in the south and the oxidation zones tend to be thicker, suggesting that the 4000 or perhaps 9000 years of time difference is sufficient to allow subtle changes to occur.

Sequence of Late Wisconsin Events

Introduction

Late Wisconsin ice crossed the Canadian boundary about 17,400 to 22,000 years ago and advanced nearly to the Spokane-Columbia River confluence.

Interaction with the glacial lake impounded by the Okanogan lobe near Grand Coulee had a profound effect on ice flow mechanics and are briefly discussed in the following sections. Continued thinning and accompanying snout retreat produced numerous kame terraces and temporary stillstands. Readvances or equilibrium flow of ice for a significant period of time produced lateral moraines and kame deltas. Only readvances or the more significant pauses in ice retreat are discussed in the following sections outlining the late Wisconsin sequence of events.

Lamb Draw (Rothlisburg) Advance (W1)

The late Wisconsin Cordilleran ice sheet crossed the international boundary about 17,400 or perhaps as much as 22,000 years ago. Ice movement was greatest in rate and extent in the larger south-trending valleys such as the Columbia. The ice thickened forcing the edge of ice to encroach and eventually bury drainage divides and to extend farther south. Ice thickness at the international boundary during the glacial maximum was over 6000 feet decreasing to a few hundred feet just north of the Spokane-Columbia confluence (Figure 2, page 12) near the Rothlisburg school site by Lamb Draw Creek. Dating of the bouldery deposits at the Lamb Draw site is difficult because the deposit was reworked by late Wisconsin floods. Thus, the Lamb Draw deposit could potentially be older than late Wisconsin. An alternate hypothesis is that the bouldery deposits are part of a large debris fan produced by catastrophic floods eminating from the narrow Spokane River canyon mouth. However, the low, subdued boulder ridges in the same area are more likely glacial than flood origin.

Catastrophic floods from glacial Lake Missoula preceded the maximum advance of the late Wisconsin(?) Columbia lobe and deposited a flood gravel with north-dipping foreset beds in the Lamb Draw area. The pebble to cobble size gravel represents very high current energy deposition that requires either no lake or a shallow glacial Lake Columbia so that the energy of the flood was not dissipated by a deep, slow moving water body. Other ramifications of this relationship are that the Purcell Trench lobe was extensive enough to create glacial Lake Missoula and its attendant outburst floods or jokulhlaups. Thus the late Wisconsin glaciers reached their maxima first in the east (Purcell Trench) and lastly in the west (Okanogan lobe).

During the W1 advance, the Columbia lobe overrode the early flood deposits and constructed a terminal moraine or perhaps a series of DeGeer moraines containing many large boulders in the Lamb Draw area. Exposures of this bouldery material occur along the right bank from Lamb Draw northward for 1-mile (1.6 km). A variety of lithologies occur in the resulting diamicton but only a few striated rocks were found. A series of low ridges form arcuate loops that extend into the Columbia Valley beneath the low water levels of the reservoir. Such moraines are normal expressions of a land-based glacier and do not form where a glacier calves into a glacial lake unless these are a type of DeGeer moraines. DeGeer moraines form at the point where a glacier floats off of its bed and deposits a poorly sorted, bouldery water-lain till. If the moraines are from a land based glacier, then subsequent floods may have reworked much of the moraine, washing out the finer matrix material, and creating a lag deposit consisting of boulders up to 9 feet (3 m) in maximum diameter.

Symmons (1882), in an early survey of the Columbia River, reports a rapids containing large boulders extending across the Columbia Valley at this site. Pardee (1916, Plate 1) shows this location as the Spokane Rapids. Large boulders occur on the left bank as well although here they seem to be a mixture of reworked till and landslide material.

Morainal material plugging two side valleys at 2200-foot (670 m) elevation some 11 miles (17.6 km) upstream above the Mitchell Point area (Wilmont Creek 15 minute quadrangle) probably correlates with the Lamb Draw boulder deposit. A correlative moraine is located across the Columbia Valley on hill 2652 (NE ¼ Section 18, T29N, R35E) just northwest of Miller Mountain. The well-developed moraine wraps around the north side of hill 2652 and can be followed for 3.5 miles (5.6 km) southeast where it loops across S.R. 22 (SW ½ NW ¼ Section 28, T29N, R36E) and extends into the main Enterprise Valley near McCoy Lake.

Farther up the Columbia Valley, about 4 miles (6.4 km) south of Fruitland, the Columbia lobe bifurcated with the major flow extending into the Enterprise Valley. The Enterprise Valley is a high, structurally-controlled hanging valley that connects the Columbia Valley with the Spokane Valley 7 miles (11.2 km) to the south. During the W1 advance ice spilled out of the Enterprise Valley into the Spokane Valley and extended westward to the Ft. Spokane area and southeastward perhaps to the Sand Flat (Turtle Lake SE, 7.5 minute) area. Boulder concentrations occur at these suspected moraine sites in the Spokane Valley. The boulders armor meander necks that extend into the reservoir near Ft. Spokane and cause a narrowing of the channel in the Sand Flat area. The age of the original boulder deposit is uncertain because of reworking by catastrophic floods. The extensive Sand Flat boulder area may contain both intermediate and late Wisconsin glacial deposits.

Neal Canyon Ice Position (W2)

The advancing Okanogan lobe flowed over the Grand Coulee damsite and reached a minimum position of 7 miles (11.2 km) to the east near Neal Canyon. This area is just east of the ice margin mapped by Flint and Irwin (1929). Large basalt and granite boulders near the intersection of Section 7, 12, 13, and 18 (T28N, R32E, Grand Coulee quadrangle) and east-dipping kame delta gravels exposed along Lake Roosevelt mark the position of the former terminus. Correlative moraines were studied in the Peter Dan Creek area by Millikan (1981).

Exposures along Lake Roosevelt in the 1360-foot (414 m) terrace record an oscillating ice front calving into a glacial lake. Poorly sorted kame-delta gravels with east-dipping foreset beds are interbedded with lacustrine sediments and record at least two oscillations of the ice front. Flint and Irwin (1939) record similar oscillations at the Grand Coulee damsite.

Castle Rock-McCoy Lake Ice Position (W3)

Continued advance of the Okanogan lobe generated a deepening lake until glacial Lake Columbia I (2400 feet, 730 m or more in elevation) formed as the ice blocked the upper end of Grand Coulee (or Grand Coulee was not yet eroded back to the Columbia Valley) and forced water to spill southward along the south rim of the Columbia Valley. The lake cut a number of strandlines which are best displayed in the Grand Coulee (15 minute) quadrangle. No thick accumulations of Pleistocene age lacustrine sediments at high elevation were found in the Columbia Valley during the course of this investigation. Other support for a high lake stand following a late Wisconsin glacial advance is provided by Millikan's (1981, p. 17-18) work near Grand Coulee where he found that the 2400-foot (730 m) strandline is cut into tills of late Wisconsin age.

The high lake was succeeded by Lake Columbia II (1700 foot terrace, 518 m) which began to form more than 13,000 years ago. The Columbia glacier must have calved extensively into Lake Columbia I but must have readjusted to a new position with the lower lake levels of Lake Columbia II. The ice front stabilization in the Columbia Valley is well marked just north of Castle Rock Creek where sandy matrix, water-lain tills and kame terrace, and kame delta deposits occur. A lateral moraine at an elevation of 1920 feet (585 m) (Wilmont Creek SW 7.5 minute quadrangle) marks the outer margin of the Castle Rock glacier near the Mitchell Spring area (Section 35, T30N, R35E) and places on upper limit to the level of Lake Columbia II. Other upvalley lateral moraines and kame terraces can be correlated with this and other ice positions on the basis of elevation and geographic position.

The Enterprise Valley lobe withdrew from the Sand Flat area in the Spokane Valley in response to the rise of glacial Lake Columbia I and built a sandy kame moraine in the McCoy Lake area in equilibrium with Lake Columbia II. Catastrophic floods flowing down the Spokane Valley were aimed directly at the Enterprise Valley and reworked the glacial drift, elongating the debris into a large, 2.5-mile (4 km) long, northwest-trending, moraine-flood bar complex. The huge bar is readily seen on the Turtle Lake NW (7.5 minute) map. The glacier initially protected the Enterprise Valley from the floods but eventually lower-energy floods may have coursed through the valley and into the Columbia Valley near O-Ra-Pak-En Creek (Wilmont Creek 15 minute quadrangle).

If large floods had spilled through the 1800-foot (55 m) elevation, Enterprise Valley, floods bars, and other major flood effects would be recognizable. Although no major flood effects are apparent in the Enterprise Valley, numerous flood units near the mouth of O-Ra-Pak-En Creek that are interbedded with varved sediments and are dipping north from the Enterprise Valley into the Columbia Valley suggest that at least some small floods flowed through the Enterprise Valley after its deglaciation. Alternately, some of these flood units could be deposited by floodwaters flowing up the Columbia Valley when ice remained in the Enterprise Valley. This very interesting section of the reservoir needs further study.

After deep floods ceased flowing down the Spokane River valley, glacial ice buried by sediment in the McCoy Lake area melted and created a kame and kettle topography, including the 100-foot (30 m) deep depression now occupied by McCoy Lake. If major floods had swept down the Spokane River valley and into the Enterprise Valley after the kettles had formed, these depressions including the McCoy Lake depression would have been filled with sediment.

The Castle Rock ice position correlates with the middle Pinedale stade of glaciation recognized by Richmond and others (1965; 1986). However, the use of the term stade is not justified if the interpretation given here is correct that this ice stabilization represents an adjustment to changing lake levels rather than to climatic events.

Hunters Ice Position (W3)

A number of lateral moraines and kame terraces occur upvalley and can be correlated with the Lamb Draw and Castle Rock events. Glacial Lake Columbia II remnants cannot be positively identified north of the Castle Rock area probably because it was succeeded by glacial Lake Columbia III (1560 foot terrace, 475 m elevation) shortly after recession from the Castle Rock ice position.

A significant stillstand of ice occurred just north of the town of Hunters (SE ¼ Section 31, T31N, R37E) where kame delta deposits grade into till and are in turn overlain by lacustrine sediments of Lake Columbia III (Figure 3, page 10). A lateral moraine that probably correlates with the Hunters ice position plugs a tributary valley and forms Clark Lake about 6.5 miles (10.4 km) upvalley at an elevation of 1920 feet (585 m). Slight recession of the ice formed a kame lake on both sides of the valley at an elevation of 1800 feet (550 m) that potentially represents a serious landslide hazard because of its high elevation.

Kettle Falls Advance (W4)

Rapid ice retreat occurred after the Hunters ice position was vacated. A number of kame terraces occur west of Inchelium where they record the final disappearance of the glacier from this segment of the Columbia Valley. The rapid, orderly retreat continued to somewhere north of Kettle Falls. Ice in the Colville Valley, a major branch valley that presently drains into the Columbia near Kettle Falls, withdrew from the Columbia Valley. A climatically-induced readvance pushed ice back to the Columbia Valley producing an end moraine near the S.R. 25 bridge (SW ¼ SE ¼ Section 36, T36N, R37E, Kettle Falls 7.5 minute quadrangle) where it crosses the Colville River. Crudely-stratified, water-lain till dips westward into the Columbia Valley at this site.

The Colville Valley glacier has been regarded by previous workers as a sublobe of the Columbia ice lobe. However, the evidence of a Colville Valley end moraine in the Columbia Valley implies that the Columbia glacier had retreated north and that the Colville lobe was independently fed by glaciers to the north. During more extensive glaciation, the glaciers did merge and some of the Colville glacier nourishment came from the Columbia lobe at that time.

The Columbia Valley lobe, and probably the Kettle River lobe, joined again and readvanced, perhaps simultaneously with the Colville glacier advance. The advancing glacier split around a bedrock ridge (Hawk's nest, Kettle Falls 7.5 minute quadrangle) with the east lobe terminating near the present Kettle Falls townsite and the west lobe flowing down the main channel to a site about 0.5 miles (0.8 km) south of the Kettle Falls bridge where glacial Lake Columbia III sediments are highly contorted and complexly intermixed with till. The advance was apparently short and did not build any substantial end moraines.

However, a substantial body of fine sediment derived from both the Columbia and Colville Valley lobes accumulated in front of the Columbia lobe. The old channel of the Columbia may have flowed along the east side of the Columbia Valley before being plugged by lacustrine and other glacial debris. The upper elevation of the glacial fill is 1600 feet (490 m) and represents the upper level of Lake Columbia III. The north end of the fill is concave upstream (Mission Bay) and outlines the edge of the ice just before it retreated more rapidly to the north. The high, steep, ice-contact north slope and the probable filled valley combine to form a serious slope stability problem that is discussed elsewhere in this report.

Marcus Advance (W5)

Ice retreat progressed rapidly again after the Kettle Falls advance. The Columbia and Kettle River lobes disjoined and retreated up their respective valleys. Another stillstand or readvance created a stationary ice front in the Columbia Valley where lodgment till, ablation till, and kame delta sediments were deposited. The ice margin is marked in the

Kettle River valley by a bouldery diamicton at Deadman Creek and in the Columbia Valley by a moraine complex about 0.5 miles (0.8 km) upvalley from the town of Marcus. The Marcus moraine is well exposed in highway and railroad cuts and in 100-foot (30 m) high landslide scars along the reservoir. The till along the reservoir is both underlain and overlain by kame-delta gravels. Lacustrine sediments from Lake Columbia III cap the till up to at least 1440 feet (440 m). The extensive 1560-foot (475 m) terrace on the right bank was probably deposited along the ice margin and is the northernmost major remnant of Lake Columbia III.

Upvalley, lateral moraines at 1760-foot (540 m) elevation along China Creek (W ½ Section 3, E ½ Section 4, and Section 33) in the Marcus (7.5 minute) quadrangle mark the lateral edge of the Marcus glacier. The nearby "Potholes" kame terrace area (1800 feet, 535 m) is probably related to the slightly older Kettle Falls advance.

Recession and downwasting continued with no major recognized pauses. The thinning ice blanket uncovered more of the buried topography and meltwater found its way across drainage divides through high passes that increase in elevation in the upvalley direction in the China Bend (7.5 minute) quadrangle. These passes include Williams Lake (elevation 1960 feet, 600 m), Swede Pass (elevation 2240 feet, 685 m), and Phalon Lake pass (elevation 2760 feet, 840 m) which all diverted meltwater ponded along the margin of the Columbia lobe into the Echo Valley where it eventually flowed into the Colville Valley about 11 miles (17.6 m) to the south.

Peaks, such as the 2627-foot (800 m) high one in Section 35 (T39N, R39E, China Bend 7.5 minute quadrangle) that were previously ice covered became nunataks as the ice continued to thin. The large Flat Creek-Town Creek valley west and north of peak 2627 became clogged with lacustrine and outwash sediments. Groundwater storage may be large in this buried valley although only a few springs discharge along the reservoir on the north end of the valley and the slopes seem relatively stable.

Numerous terraces at many levels occur along the upper Columbia Valley and represent temporary ice positions as ice downwasted. Other terraces below the Lake Columbia III level (1560 feet, 475 m) contain lacustrine sediments (Lake Columbia IV?) and indicate that a low level glacial lake persisted until the glacier had at least reached the international border. As the Okanogan lobe retreated, decreasing base levels allowed the Columbia River to partially clean out its valley of sediment and to cut additional levels in the lower part of the valley. Coarse gravels cap many of the lower terraces and reflect fluvial conditions as glacial Lake Columbia because shallower.

San Poil Lobe

Pardee (1918, p. 52) recognized two ages of glaciation in the San Poil as well as the Columbia Valley. He believed that the younger (late Wisconsin) advance terminated near Iron Creek, in a position about 0.3 miles (0.48 km) farther north than the ice front proposed in this paper, 10.5 miles (16.8 km) north of Flint's (1936), 16.5 miles (26.4 m) north of Flint and Irwin's (1939), 0.4 miles (0.64 km) south of Richmond and others' (1965) ice front, and 0.25 miles (0.4 km) south of Fryxell's (1959). Waitt and Thorsen (1984) and Atwater and Rinehart (1984) placed their ice margin about 1 mile (1.6 km) south of Pardee's. The major discrepancy here is Flint's (1936) and Flint and Irwin's (1939) work because they considered all of the deposits to be late Wisconsin in age and they did not accept the catastrophic flood hypothesis. Thus, they were unable to recognize that coarse, bouldery deposits farther south were older tills reworked by floods.

The recognition here that the late Wisconsin ice front in the San Poil Valley is located just south of Brush Creek (Keller SE 7.5 minute) near the boundary of Sections 17 and 18 with Sections 19 and 20 is based on the presence of large erratics on the Cow Creek ice-contact terrace to the north (elevation 1720-1840 feet, 525-560 m), the presence of a diamicton interpreted as a late Wisconsin till near Brush Creek (NW ¼ Section 17) and the presence of deeply-weathered bedrock in areas to the south. A well-developed late Wisconsin moraine in Bridge Creek (elevation 2160 feet, 660 m) about 9 miles (14 km) to the north is consistent with the proposed ice terminus.

APPENDIX B

Terraces and Bars

Previous Work

Pardee (1918) recognized the abundance of terrace remnants in the valleys of the Columbia and its tributaries including two prominent levels at 1700 to 1800 feet (518-549 m) and 1400 feet (427 m). He also recognized intermediate and lower levels. However, he did not recognize that these terraces were controlled by a glacier dam but instead believed that the land subsided under the weight of the glacier and following deglaciation, each level formed near sea level as the land uplifted towards its present level (Pardee 1919, p. 42). The glacially-derived silt filled the resulting lake or estuary and progressive uplift would account for other terrace levels. The terrace sediment was were named the Nespelem silt it was recognized as being deposited directly on top of glacial drift during the deglaciation process.

Bretz recognized that the Wisconsin age Okanogan ice lobe blocked the Columbia Valley (1923, p. 592) and that the "seasonally banded" (1923, p. 606) Nespelem formation may have been deposited in the ice-dammed lake although he does not completely discount Pardee's idea of lowering the area to sea level.

Flint (1935 and 1936) describes the 1700-foot (518 m) Nespelem silt terrace and recognizes that it terminated against the Okanogan ice lobe downstream near the Nespelem River. He also believed that a higher fill in the Spokane Valley was produced by an ice dam near the Spokane-Columbia confluence. The silt accumulations in the glacial lakes were locally mixed with abundant and coarser sediment contributions at Chamokane Creek (lower Colville Valley), the Columbia-Spokane confluence, and the mouth of the San Poil River valley. Lower terraces represent fluvial dissection as the lake level was slowly lowered.

Although Flint (1936, p. 1873) recognized the intermediate terrace (1400 feet, 427 m) of Pardee (1918), he believed that it was restricted in distribution to the Nespelem-Grand Coulee segment of the river. He failed to recognize important intermediate terrace remnants near Ft. Spokane and along the Spokane and upper Columbia River valleys. He does not discuss the prominent 1560-foot (476 m) terrace remnants along the Columbia-Spokane Valleys and seems to believe that the 1700-foot (520 m) terrace "is graded to the hanging floor of Grand Coulee" (Flint 1936, p. 1858 and 1868) even though the floor is now at 1530-foot (466 m) elevation. Perhaps he meant a previous hanging floor level of Grand Coulee. Lacustrine sediments in the Grand Coulee near Steamboat Rock occur from at least 1580 to 1640 feet (480-500m) indicating that a higher base level did occur at one time. Whether the 1700-foot (520m) base level was controlled by bedrock or debris is not discussed by Flint. Further, he interprets sediment in the lower part of the Columbia River valley near Ft. Spokane as till and lacustrine silt overlain by fluvial sand (Flint and Irwin 1939, P. 1870). This paper interprets the lower cross-bedded sand and gravel as glacial sediment reworked by floods and inset against the older lacustrine terrace. Flint, of course, had an advantage in that he had outcrops available in the lower valley that are now inaccessible because of the water level in the reservoir. Thus, he may be basing some of his conclusions on information not reported in his publications and no longer accessible.

Flint and Irwin (1939) describe a detailed stratigraphic section compiled during dam construction. The sediments record the formation of a glacial lake in the Grand Coulee damsite area as the Okanogan ice lobe enlarged. Ice then overrode the area and was followed by a return to glacial lake sedimentation as the ice retreated. Again, low elevation gravels with downstream-dipping foreset beds occur both upstream and downstream from the dam. These cannot be readily explained as deposits from the retreating Okanogan ice because the glacier retreated northward in the downstream direction. Flint and Irwin (1939, p. 672) suggested that residual ice, detached from the main glacier, furnished the necessary meltwater and debris to form the gravel unit. However, late stage, catastrophic floods reworking glacial materials is a better explanation.

Jones and others (1961) studied the landslides and their contributing factors along Lake Roosevelt. They recognized the influence of the type of sedimentary material to landslides and noted that the term Nespelem silt is misleading because perhaps 25 to 50 percent of the valley fill material in the Columbia River valley is sand and gravel (Jones and others 1961, p. 4). Further, rather than the Nespelem silt being the product of one lake stage as Pardee (1918) believed, they propose that the history was more complex. Jones and others (1961, p. 28) suggest that during late Wisconsin time an early lake formed, drained, and the river cut down to near its present level before a second lake formed. The stratigraphic evidence used for these conclusions can better be interpreted as a lake overridden by ice and the return of the lake as the ice retreats back over the site.

Jones and others (1961, p. 14) recognize evidence in the Reed Terrace area near Kettle Falls of a lower lake that was also dammed by the Okanogan lobe. Three lower terraces in the same area are attributed to downcutting by the Columbia River after the Okanogan lobe ceased to dam the lake.

Based on the elevation of kame deposits, erratics, and a late Wisconsin end moraine near Grand Coulee, Richmond and others (1965, p. 237) assign a minimum elevation for the late Wisconsin glacial Lake Columbia of 1950 feet (595 m). The Nespelem level (1700 foot terrace, 520 m) is considered to be a late stage of Lake Columbia whose elevation was controlled by the rock floor of Grand Coulee and the Okanogan ice downstream. They do not mention that the rock floor elevation today is 1530 feet (465 m). Thus significant changes in base level that are not discussed by Richmond and others (1965) must have occurred. The removal of the Okanogan ice dam produced lower lake elevations. They also note that Waters (1933) recognized that an abrupt draining of Lake Columbia would produce flooding of downstream areas.

Millikan (1981) studied the Peter Dan Creek area near Grand Coulee Dam and recognizes 2500-foot (806 m) and 2400-foot (775 m), lake levels. The 2500-foot (805 m) level is a highly dissected wave-cut terrace found at two localities in the Grand Coulee quadrangle that Millikan (1981, p. 13) equates to a pre-late Wisconsin glaciation. A lake at this elevation would spill out of the Columbia River valley through Jump Canyon (SW ¼ Section 9, T27N, R34E, Wilbur quadrangle), the Creston-Telford scabland channel, and other areas along the Spokane Valley unless these channels were not cut below 2500 feet (805 m) when the high lake existed. Very likely, the 2500-foot (805 m) level is pre-Wisconsin.

A 2400-foot (775 m) elevation wave-cut terrace is cut into late Wisconsin tills at Peter Dan Creek indicating that the lake here reached its maximum elevation sometime after the maximum advance of late Wisconsin ice (Millikan 1981, p. 17-18). A similar strandline is reported in the nearby San Poil River valley (Cochran and Warlow 1979) indicating that the lake was widespread.

Also in the Peter Dan Creek area is the 1700- to 1800-foot (550-580 m) Nespelem terrace from which were collected samples of the 13,000 year B.P. Mt. St. Helens "set S" ash. Samples of pre-glacial bark and wood collected by Millikan (1981, p. 20) that underlie the terrace are 23,898±1040 years old.

Kiver and Stradling (1982a and 1982b) presented an early analysis of Columbia and Spokane Valley terraces from Rocky Reach dam to Canada and Idaho before beginning the more detailed studies of the present shoreline study. Using topographic maps and reconnaissance level fieldwork, some 16 terrace levels (not including those marked by wave-cut terraces) were recognized. Several of these upstream from Grand Coulee Dam seemed prominent. By allowing for post-glacial deposition of alluvial fans and colluvium and for minor isostatic adjustment we now recognize four important late Wisconsin terrace levels. These are: (1) 1680 to 1760 feet (510-535 m); (2) 1560 to 1600 feet (475-490 m); (3) 1400 to 1480 feet (430-455 m); and (4) 1320 to 1360 feet (405-420 m).

The high strandline levels (2400 feet, 730 m and 2200 feet, 670 m) were controlled by an ice dam or bedrock in the Grand Coulee, the 1700-foot (518 m) level by a bedrock lip ? than 1700 feet (518 m) in Grand Coulee, the 1560-foot (475 m) level by the bedrock lip after floods had lowered the lip or by a moraine southwest of Steamboat Rock, and the more extensive lower terrace levels by the elevation of the Okanogan lobe or downstream debris dams blocking the Columbia River valley near the Nespelem River and Omak Trench areas.

Conclusive evidence that at least 15 late Wisconsin catastrophic floods separated by a few decades of normal glacial lake sedimentation must have swept through the Spokane

River valley was reported by Stradling and others (1980), Kiver and Stradling (1981), and Rigby (1981). The logical conclusion of this discovery is that these same floods must have affected the lower Columbia River valley as well.

In the lower San Poil River valley, Atwater (1984; 1986) found that the sediments in the 1700-foot (520 m) terrace have the same type of alternation of varved lake sediments and graded, high energy flood units as those reported in the Spokane River valley (Stradling and others 1980 and Waitt 1984). A minimum of 15 floods, and possibly many more (Atwater 1984) occurred in the Lake Columbia area. These catastrophic events produced significant influences in the sequence and also in the engineering characteristics of sediments found in the lower reservoir area.

Waitt and Thorsen (1984, p. 57) recognize, as most previous workers do, that a high stand of glacial Lake Columbia was followed by lower elevation lakes. The high stand, glacial Lake Columbia I (2400 feet, 732 m) was held in by the floor of the upper Grand Coulee which had not yet been cut through to the Columbia River valley and/or by the fully extended Okanogan lobe that blocked the completed coulee (Waitt and Thorsen, p. 57 and 64). Withdrawal of ice from Grand Coulee or flood alcove retreat established Lake Columbia II (1680 feet, 512 m) and later lower lake levels are attributed to Lake Brewster (1180-1300 feet, 360-396 m) which was dammed by the Okanogan lobe or a debris dam well downvalley from Grand Coulee Dam. The 1395-foot (425 m) terrace that extends north of Kettle Falls is postulated to be an isostatically uplifted segment of the 1300-foot (396 m) Lake Brewster terrace (Waitt and Thorsen 1984, p. 64).

No major 1300-foot (396 m) terrace remnant is apparent along the reservoir, however 1360-foot 9415 m) and 1440-foot (439 m) terraces are present (presumably the isostatically raised remnants of Lake Brewster). These levels can be traced throughout the reservoir and no clear indication of any significant differential isostatic change is apparent. Waitt and Thorsen (1984) are uncertain whether Lake Columbia I was late Wisconsin or pre-late Wisconsin in age and whether the bedrock lip and/or the Okanogan ice impounded Lake Columbia I. They do believe that the Lake Columbia I level was reached at least briefly during late Wisconsin time. They attribute lacustrine sediments in the Spokane area to the high stand of Lake Columbia I. This short-lived lake is unlikely to account for the 600 or so years of lacustrine sediments in the upper Spokane Valley and its tributaries. Waitt and Thorsen failed to recognize that the ice dam from the Enterprise Valley was sufficiently thick to produce a long-lasting, deep lake that extended in the Spokane area.

Other difficulties with the Waitt and Thorsen (1984) model include lowering the coulee lip from 2400 feet (732 m) to 1530 feet (466 m) and having the new base level control deposition of the 1700-foot (518 m) terrace level. To explain this they propose that the lake terraces in the Columbia River valley were later isostatically raised from near the 1530-foot (466 m) level to the 1680-foot (512 m) level while the 1530-foot (466 m) level in Grand Coulee remained unchanged. However, the 1680- to 1720-foot (512-524 m) terrace appears to be a major terrace that occurs in many sections of the San Poil and Columbia River valleys. Many of these areas were ice free during the late Wisconsin and should not have experienced any isostatic rebound. It is more likely that there were a number of intermediate base levels between 1530 to 2400 feet (232-524 m) as catastrophic floods continued to deepen the coulee. Some of these were bedrock base levels and one or more may be related to the moraine(?) near Steamboat Rock first recognized by Bretz (1932) that was later reworked by catastrophic floods into a flood bar.

Genesis

The internal composition of the terrace and bar surfaces adjacent to Lake Roosevelt usually reflects a compound genesis. Although glaciolacustrine silt and clay account for much of the sediment volume, sand units are very common and locally gravel is a major component. In the upper Columbia River valley (above the Spokane River confluence), glaciofluvial sand and gravel with minor amounts of tributary valley sediment and glacial till become more important. The lower Columbia River valley has fewer deposits of gravel and more abundant sand units, mostly derived from catastrophic flows of water from Lake Missoula. The sand-silt ratio increases in the Spokane River valley where contributions from the Lake Missoula floods become even more important. More detailed discussions of each terrace unit is provided in the "Summary of individual Quadrangles" section.

Glaciolacustrine Deposits

Lacustrine sediment accumulated in lakes held in by the Okanogan ice lobe and in local, ice-margin lakes. During ice retreat lakes at progressively lower elevations formed in the Columbia River valley and its tributaries and dissection of the fill towards new base levels progressed. Except for the 1320- to 1360-foot terrace, no evidence of trenching and backfilling of the valley fill was recognized.

Sediments that accumulated in the lakes show the typical sedimentologic characteristics of annual deposits known as varves. A summer layer of coarse silt or fine sand is overlain by a winter accumulation of fine silt and clay that occurs when the glacial lake is frozen or non-turbulent because of low inflows of meltwater. The entire varve tends to be normally graded (upward fining of sediments). The thickness of a couplet ranges from less than an inch (2.5 cm) in the quieter parts of the glacial lake to over 3 feet (1 m) closer to the edge of the ice. The usual thickness is closer to the thinner end rather than the thicker. Varve thickness also tends to decrease higher in the stratigraphic section as a result of the lake filling up towards its surface or perhaps due to a decreasing sediment supply as the glacier retreats farther away from a given site. The lacustrine facies grades into coarser outwash, delta, or kame delta sediments towards the front of the retreating glacier.

Lacustrine sediment can also form in kame terrace and in glacier-dammed tributaries. Mixtures of coarser materials from outwash and other sources are more likely in the kame terrace environment. For example, the 1800-foot (549 m) kame terraces along both valley sides that extend some 6 miles (9.6 km) north of Cedonia in the Hunters NW (7.5 minute) quadrangle are mostly coarse silt with very few clay layers. Thus, the higher energy conditions developed a coarser, more permeable sediment that is less susceptible to mass movement in spite of its relatively high relief.

The lacustrine materials were mapped as Qlc where clay and/or fine silt dominate and the permeability of the material is low. The coarser silt or sand sections that show no visible evidence of water perching were mapped as Qls or Qlm. Where doubt exists, the materials were mapped as Qlc or Qlz.

Where more permeable silt or sand deposited in a lake environment is interbedded with clay or fine silt, the symbol Qlz was used. The sand layers in the Qlz materials in the lower Columbia River valley are often flood caused and could be mapped as Qfs. However, since numerous flood units interbedded with lake clays often exist in one exposure, the necessary symbols would be too numerous to show on the map. Where such exposures have been examined in some detail, a numerical subscript is added to designate the number of impermeable units. For example, if 10 impermeable units are discovered in an exposure, the map symbol used would be Qlz10 (i.e., at least 10 individual sets of lacustrine clay and/or silt units exposed). In the upper Columbia River valley flood units can be traced perhaps up to the Hunters area where their flood character becomes unrecognizable from the plane bedded lacustrine sand from ice front, side valley, or storm activities.

Primary structures are features that form during or shortly after deposition and include various types of bedding, varves, grading, current features, etc. Of interest in the lacustrine sediments are various types of contorted bedding representing sediment disturbance by gravity, ice over-ride, or loading of sediments on top of saturated or nearly saturated fine sediments. All types and combinations of origins occur except that ice over-ride is not as common as Flint (1936 and 1937) and Jones and others (1961) suggest.

Contorted bedding in the lacustrine sediments seems to occur mostly through overloading of saturated sediments. Rapid rates of deposition, where catastrophic flood sediments or sediment close to the ice front rapidly bury clay-rich layers, can cause the clay to mobilize and intrude into the overlying sand or silt bed.

Zones of highly contorted sediments are, of course, found in most recent landslides where rotational movement occurred. Contorted zones in the terrace sediments due to more ancient landsliding occur in the Ft. Spokane (Lincoln 15 minute quadrangle), Nine Mile (Wilmont Creek 15 minute quadrangle), Reed terrace (Bangs Mountain 7.5 minute quadrangle), and other areas. They can be positively identified as slide caused if one can observe the surface of rupture beneath the contorted zone (see Figure 3, Jones and others 1961) or the direction of movement of the sediment, as determined by drag folds and other deformation features, is towards the axis of the valley.

Many examples of landslide debris disconformably overlain by non-contorted lacustrine sediment indicate that some slides occurred subaqueously during the Pleistocene. Some sediment was deposited directly against ice and slid as the ice support melted away. The ice contact area in Mission Bay near Kettle Falls has numerous examples of these small, subaqueous slides.

Also, in the same area and especially farther north in the Marcus quadrangle (NW ¼ Section 27, T37N, R37E) are small anticlinal and synclinal structures as much as 150 feet (46 m) across that are probably drapes of sediment over buried mounds, ridges, or valleys. In one case, a pebbly-cobble unit projects above reservoir level where varved sediments drape over the gravel mound. Contortion and fracturing in the varved sediments were produced when the wet, plastic sediment slid down the mound flanks.

The only definite example of contorted beds due to ice shove is found in the Bangs Mountain quadrangle (NW ¼ Section 14, T36N, R37E) where lacustrine units are shoved downvalley and are complexly intermixed with till.

Glaciofluvial Deposits

Fluvial processes are important in kame terrace and outwash environments. Numerous kame terraces formed, particularly during the deglaciation process as many changes in ice elevation occurred. A valley or outwash train is a deposit produced by a fluvial system. Usually the system carries a very large sediment load from an ablating glacier and extends downvalley for a considerable distance. This type of system only forms where a glacier terminates on land. Thus, this type of deposit is not very important in the Lake Roosevelt area because glacial Lake Columbia outlasted the Columbia lobe until sometime after it retreated into Canada. When Lake Columbia ceased to exist or shallowed sufficiently, then subaerial fluvial processes began to exert their influences. Outwash must have been deposited at this time and many of the fluvial surfaces capping the lower terraces are considered very distant outwash.

Coarser materials are deposited near the ice front and finer debris is carried away from the front of the glacier. This tendency can be seen locally where outwash or kame delta surfaces are preserved such as in the Brush Creek, Castle Rock, Hunters, and Marcus moraine areas. In the Castle Rock ice margin area, the kame terrace at 1800-foot (549 m) elevation near Six Mile Creek (Lincoln NW 7.5 minute quadrangle) grades steeply down to the 1760-foot (537 m) level a mile to the south. Gravels correspondingly grade from small boulders at higher elevations closer to the ice front to small cobbles to the south.

The kame delta, and especially the kame terrace environments, are particularly important in the upper Columbia River valley. Meltwater reworks debris, sometimes of boulder size, that is freed from the ablating ice (e.g., Fruitland kame terrace in the Hunters 15 minutes quadrangle, 1800 feet, 549 m). Deposition onto ice also creates an ideal situation for kame and kettle topography to form.

All sediment deposited from meltwater streams is mapped as Qog (Quaternary age outwash gravel) or Qos (Quaternary age outwash sand). No differentiation between kame terrace and kame delta environments was made. Coarser sediment from tributary valleys was mapped as stream alluvium (Qa_l) because it is usually not glacier generated. Textural characteristics of the gravels, where known, are shown by numerical subscripts.

Glacioflood Deposits

The sudden release of a substantial quantity of water from a glacier is called an outburst flood or jokulhlaup. Moderate to small floods occur in presently glacierized areas in Alaska, Mt. Rainier National Park, and elsewhere. One might expect such events in a glacierized Columbia River valley. Where such an extensive area of moderate to high relief and complex geography is glaciated, numerous ice marginal lakes that could catastrophically fail often form. The effects of moderate to small floods would be greatly muted by the stabilizing influence of glacial Lake Columbia and would be difficult to detect in the sedimentary record.

However, a unique complication of geologic events occurs in the Lake Roosevelt area because of the very large, catastrophic floods that affected the system. The unique arrangement of a large south trending glacial valley (Purcell Trench) in northern Idaho intersecting with a major east-trending valley (Clark Fork River valley) permitted the Purcell lobe to impound a lake containing over 500 cubic miles of water (Lake Missoula). The deepening lake continually reduced the load stress of the ice on the underlying valley floor until hydrostatic pressure was sufficient to force water along the base of the glacier and to emerge at the glacier snout. Enlargement of this subglacial pathway occurred by a piping process and resulted in one of the largest known releases of impounded water ever to occur. The water flowed southward and westward through the Spokane and lower Columbia River valleys spilling out of these valleys and cutting a complex series of channels across the Columbia Plateau known as the Channeled Scabland (Figure 7, page 15). Grand Coulee is the most spectacular of the many channels that were formed. Flows of 9.5 cubic miles/hour (40 cubic kilometers/hour) are estimated for a narrow section of the Clark Fork Valley in Montana and 1.84 cubic miles/hour in the upper Spokane River valley (Baker 1973, P1.1).

The effects of these floods in the Channeled Scabland area have been well documented by Bretz (1923, 1956, and 1969, and others). Where large volumes of water poured across a subaerial landscape, various depositional bars with particular morphologic and sedimentary characteristics form. In the Lake Roosevelt area flood bars are best displayed in the Spokane River valley in the Lincoln (15 minute), Turtle Lake (15 minute), and especially the Little Falls (7.5 minute) quadrangles. Distinctive pendant bars show up well on air photos and topographic maps in areas such as SE ¼ section 19, S ½ Section 20, N ½ Section 29, NE ¼ Section 30, T27N, R39E; and the N ½ Section 16, S ½ Section 18, T27N, R39E in the Little Falls quadrangle. Giant current dunes occur in the Little Falls quadrangle (SW ½ Section 24, T27N, R38E: SE ¼ Section 36, T27N, R38E) and the Lincoln quadrangle (SE ¼ Section 8, T28N, R36E).

The ratio of flood-contributed sediment to lacustrine sediment decreases below the mouth of the Spokane River where the valley width at reservoir level is five times wider below the confluence than in the Spokane River valley above the confluence. The valley depth is also greater below the confluence. The flood energy greatly dissipates under these conditions and flood deposits become thinner. Flood bars are poorly developed below the Spokane-Columbia confluence. The flood sediment is mostly sand size except where the lake was shallow, absent, or where coarse material from previous deposits by ice or fluvial processes was available for reworking.

The effects of floodwaters entering a deep glacial lake are less well known than those deposited subaerially in the Channeled Scabland. However, the effects of these giant flows of water flowing through the sinuous course of the lower Columbia River valley is very noticeable because they produced intense erosion at the outside of river bends (Figure 31). Studies of what are known as slackwater sediments (flood deposition in protected or semi-protected geomorphic locations) deposited into a glacial lake in Latah Creek near Spokane were reported by Stradling and others (1980) and studied in much greater detail by Rigby (1982).

The characteristics of the sediments in Latah Creek and in other areas of the Columbia-Spokane Valleys are similar to those produced by turbidity currents (subaqueous density currents). The sediments and their primary structures record the rapid movement of sediment by gravity or current processes followed by decreasing flow energy. A specific sequence of sediment sizes and depositional

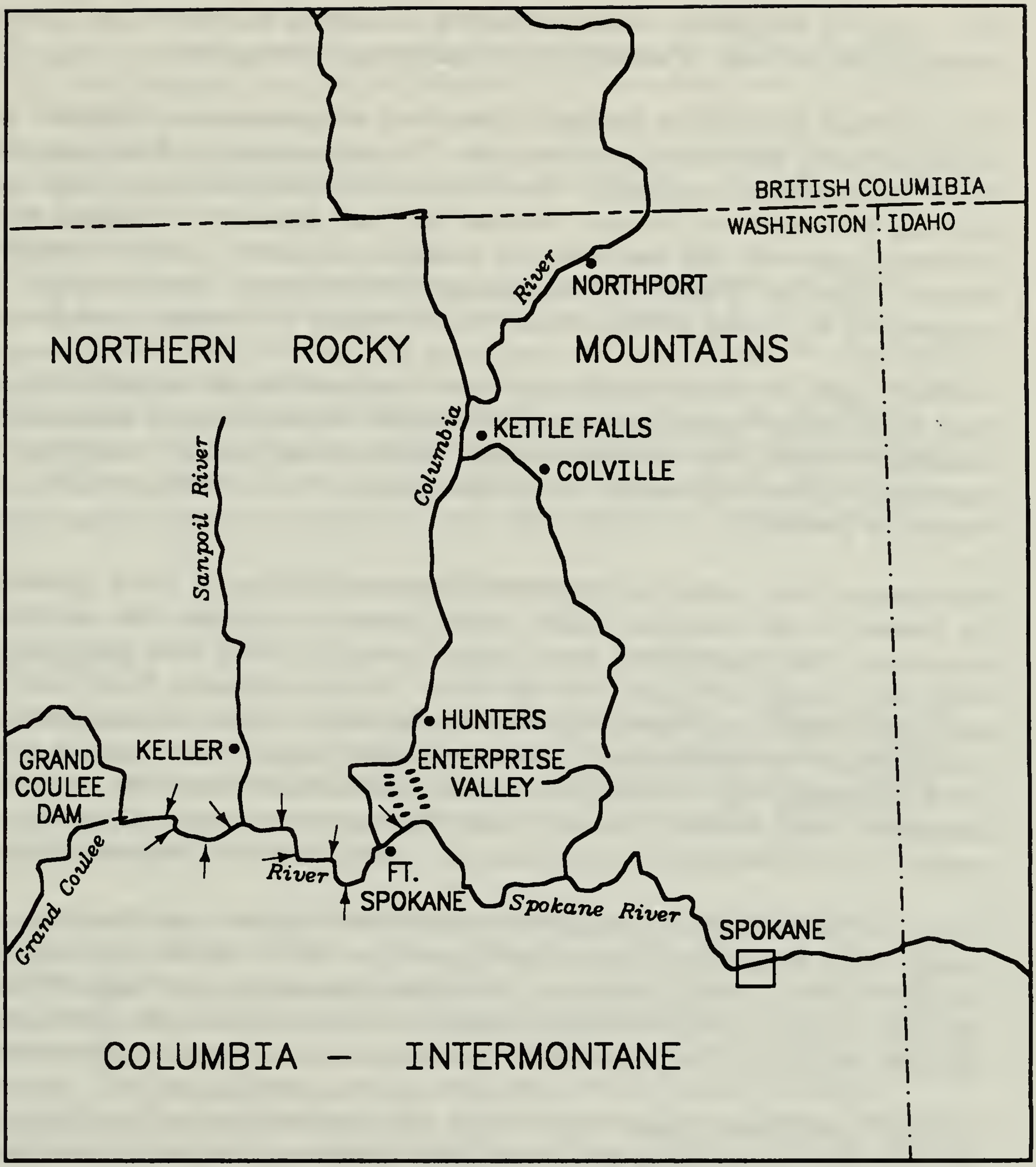


Figure 31 – Areas of intense catastrophic flood erosion along lower Spokane and Columbia River valleys. Arrows indicate outside of major river bends where intense flood erosion helped remove sediments.

structures form, similar to those generated in flume tank experiments. An idealized turbidite described by Bouma (1962) consists of five distinct units, all of which need not form in every situation. Most commonly, units B, C, and D make up the flood deposits found in the Lake Roosevelt area.

More useful in recognizing flood units are rip-up clasts at the base of the flood unit and ripple lamination, both of which imply a high energy current flow.

Flood currents generated in the glacial lakes were often erosive and removed all or part of an underlying varve and older flood unit. Thus the number of flood units recognized should be considered a minimum. The tops of many flood units have a fine, oxidized sand unit that marks the boundary between two flood units. If the oxidized zone is completely removed, only one flood unit would be recognized. Another possible source of error is that not all sand units are necessarily flood caused. Intense storms, side valley contribution, etc., could generate a sand unit that could be mistaken for a flood unit.

Although sandy flood units interbedded with lacustrine clay and silt sediments are most likely to be caused by a flood from Lake Missoula, the possibility of other glacial lakes somewhere in the Columbia River drainage system failing is high. Thus, some catastrophic floods from smaller ice-dammed lakes in the Columbia, San Poil, and other valleys are possible.

For example, both in the San Poil River valley and the Wilmont Creek quadrangle near the entrance to the Enterprise Valley, ripple foresets are oriented both upvalley and downvalley. This might reflect flood currents moving upvalley from the Columbia River valley and a return flow back down the valley. Upvalley Missoula flood currents and downvalley flowing local jokulhlaups or changing eddy currents during a Missoula flood could produce both upvalley and downvalley ripple foresets. In the case of the Wilmont Creek quadrangle near O-Ra-Pak-En Creek, flood currents might flow into the Enterprise Valley from the Spokane River valley and create downvalley currents in the segment of the Columbia River between Ft. Spokane and the Enterprise Valley.

Except for the flood gravel beneath the Lamb Draw diamicton and the coarse unit found beneath thick lacustrine deposits in the Turtle Lake SE 7.5 minute quadrangle (NE ¼ Section 23, T27N, R37E), most flood gravel units formed very late in the Wisconsin, after the Columbia River lobe had retreated far to the north and the Okanogan lobe had retreated enough to allow only shallow lakes such as Lake Columbia IV to exist.

The flood gravel units require high energy, upper regime flow, and are mapped as Qfg. The catastrophic flood must have encountered either a shallow lake or a valley devoid of a lake to produce the crudely bedded, poorly sorted gravel deposit. Frequently, a coarser zone occurs just above the base of a flood gravel deposit that suggests a lag produced by subsequent floods. Thus, flood gravels displaying lag concentrates represent more than one flood.

Again, numerical subscripts after Qfg describe the major clast size or sizes of the sediment. Carbonate cement has partly to completely indurated many of these gravels. Cementation is most common in the lower Columbia and Spokane River valleys where a drier climate prevails.

In deeper glacial lake conditions, or perhaps when larger floods deepen the water column, sand units form during flooding as discussed in the section on glaciolacustrine sediments. In a few instances, such as the 1900-foot (585 m) terraces near Ft. Spokane (Lincoln SE 7.5 minute quadrangle), the flood sands dominate and the unit is mapped as Qfs. More commonly the sand is interbedded with lacustrine silt and clay and is mapped as Q1z. The Qfs symbol is very useful in describing units shown on measured sections or on the photostratigraphy overlays.

Most of the sand units in the lower Columbia and Spokane River valleys are flood caused. The maximum number of interbedded flood units identified so far is 15 although Atwater (1984; 1989) believes that many more, perhaps 89, may be represented in the section of sediments in the San Poil River valley. Because some of the flood units in the San Poil River valley have downvalley-directed current ripples, the possibility exists that local floods from the San Poil River valley rather than Lake Missoula floods may have generated some of these floods. Another possibility is that the superposed sections in the San Poil valley may represent more than one age of multiple floods.

Correlation of Terraces

Elevation of Terraces

Preliminary correlation of surfaces was done using elevation relations. The assumption here is that a changing base level provided the major elevation control. Other factors influencing terrace elevations would include closeness to former ice positions, isostatic effects from ice loading and unloading, and deposition of fan and other debris from tributary valleys and valley sidewalls.

The more important, longer lasting Pleistocene age base level controls were the elevations of the lip of Grand Coulee and the position of the Okanogan ice lobe that blocked the Columbia River valley downvalley from the present Grand Coulee damsite. The Columbia River lobe had retreated to Canada while the Okanogan lobe or debris dams still impounded lower elevation lakes in the Columbia River valley during very late Wisconsin times. The lake surfaces acted as base levels towards which sediments accumulating in the lake attempted to reach. Thus, the level of the sediments provides a minimum estimate of the lake elevation. Generalized terrace profiles along the Spokane River are shown in Figure 32 and those for the Columbia River in Figure 33.

A temporary base level control in the Columbia River valley system was the Enterprise Valley ice lobe damming the Spokane River valley near McCoy Lake and created glacial

Lake Spokane. Ice and the resulting lake reached at least the 2200-foot (671 m) level on the south side of the lower Spokane River valley and perhaps the 2440-foot (744 m) level if the large spillway on the south end of Lilienthal Mountain (SW ¼ Section 25, T28N, R36E, Turtle Lake NW quadrangle) was used not only by the Missoula floods but spillover from glacial Lake Spokane as well. The resulting lake backed up into the Spokane area and inundated the Little Spokane River basin (Kiver and Stradling 1982). The elevations of Lake Columbia I are also high enough to account for these far upvalley sediments.

The Glacial Lake Columbia II terrace occurs in the Spokane River valley indicating that the ice barrier holding Lake Spokane was removed by Lake Columbia II time (Figure 32). Terrace levels between 1800 to 2000 feet (549 to 610 m) are common only in the Spokane River valley all the way into Spokane but have few counterparts in the Columbia River valley. Thus, these terraces reflect Lake Spokane levels or perhaps flood deposition on top of Lake Columbia terraces.

Faint and poorly-developed, non-paired terraces cut into the valley fill throughout the Lake Roosevelt area are temporary lake levels or brief positions of the Columbia River as it cut through the fill. Fluvial terraces can only form when lake levels lower or ice withdraws sufficiently upvalley so that a fluvial segment exists between the ice front and the upper end of the lake. After the Columbia Valley ice had withdrawn to Canada, and debris dams were removed from the Columbia Valley; downcutting from the Lake Columbia IV level to the pre-dam river level occurred. In the Spokane River valley a steeper gradient occurs upvalley from Lake Roosevelt and the glaciers were much farther removed, thus, fluvial components are better developed as seen in the steeper gradient upvalley profiles (Figure 32). Meandering stream segments occur in and near Spokane and fluvial terraces grade into the 1700-foot (518 m) Lake Columbia II and 1600-foot (488 m) levels.

Shorter duration base levels are indicated by strandlines in the Grand Coulee and west part of the Wilbur (15 minute) quadrangles. In the Peter Dan Creek (Millikan 1981, p. 13), a 2500-foot (762 m) strandline pre-dates late Wisconsin moraines. A 2400-foot strandline cuts into late Wisconsin moraines and is therefore late Wisconsin in age. More extensively preserved are 2000- to 2300-foot (610 to 700 m) strandlines near Spring Canyon (Section 20, T28N, R31E), Neal Canyon (Section 19 and 30, T28N, R32E), Swawilla Basin (Section 10, T28N, R32E), and Spiegle Canyon (Section 36, T28N, R32E). No other strandlines are known to the east although Flint (1936, p. 1957) reports 2150- to 2200-foot (655 to 671 m) strandlines near Nine Mile Falls up the Spokane River valley. The shortness of time at any one elevation, the rapid vertical fluctuation of strandline levels, and the lack of thick lacustrine sediments at these elevations suggests that an ice dam near the margin of a glacier was the cause. The

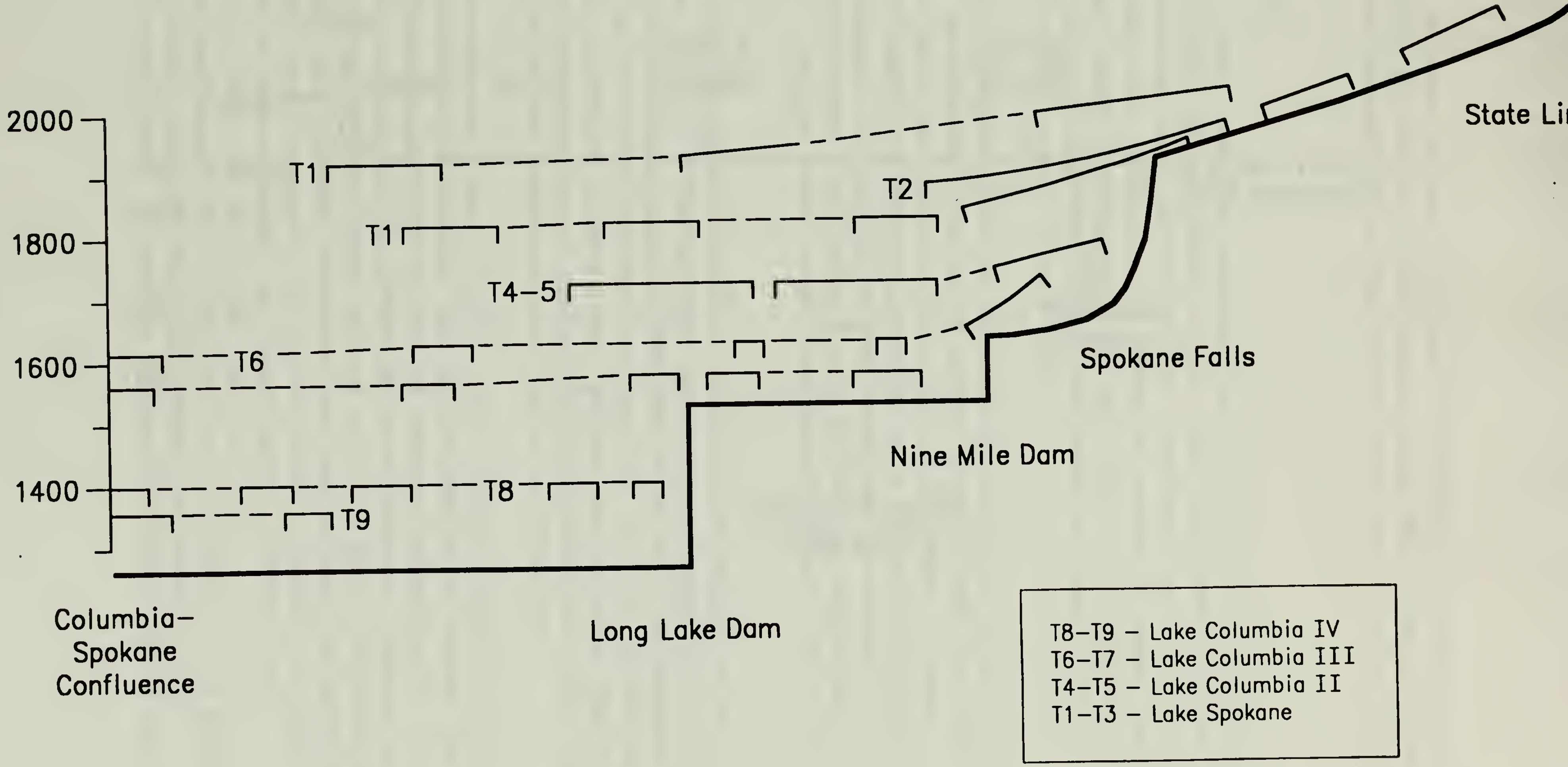


Figure 32 – Generalized Spokane Valley Terrace Profiles. Modified from Kiver and Stradling, 1982.

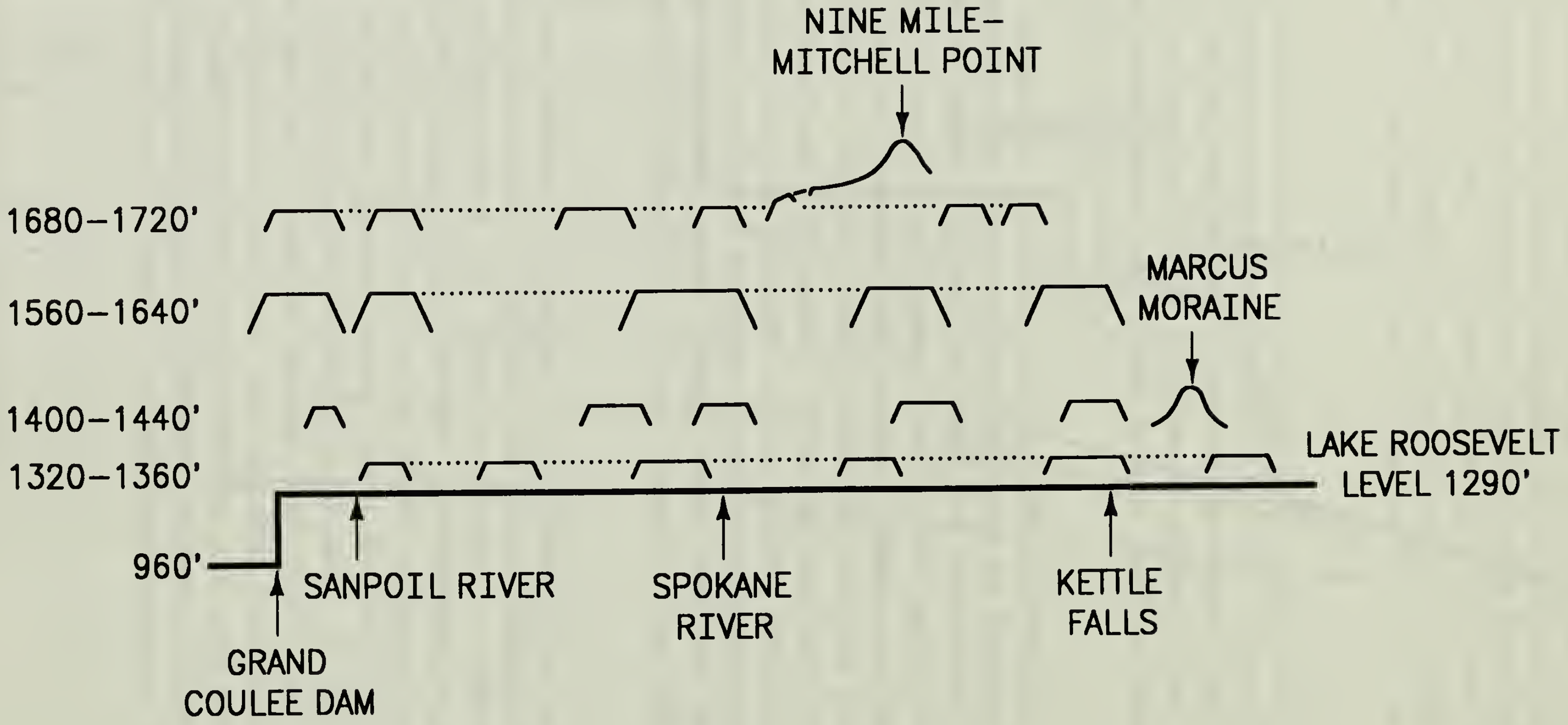


Figure 33 – Generalized Columbia River Terrace Profiles.

likely location of the ice dam was in the Grand Coulee where ice moved across the coulee and abutted the 2400-foot (732 m) high east coulee wall. Although the lake level fluctuated greatly, persistent terrace levels indicate that ice dams or bedrock dams were long lived.

Isostatic Effects

Loading of the earth's crust causes subsidence that is proportional to the load mass and the length of time that the load remains in place. Some of the crustal depression is due to an elastic component and some involves deeper adjustments that occur in the mantle beneath the earth's crust. The best way to measure the amount of isostatic change is to study strandlines created by wave action at the lake surface. Such strandlines are horizontal at the time of their formation and warp upward as differential crustal readjustments occur to conditions after unloading.

Lake Columbia I strandlines (older late Wisconsin age) at 2000- to 2300-foot (610 to 700 m) elevations are located in a west-trending segment of the Columbia River valley from Grand Coulee Dam to just south of the Keller Ferry in the Wilbur (15 minute) quadrangle. It is difficult to locate each strandline in the field and many cannot be observed on airphotos. Ideal lighting and shadow conditions are necessary to even see some of these strandlines. Their location along a west-trending valley segment is inappropriate to recognize crustal rebound which would be greatest along a north-south line.

Reoccupying first order elevation stations, if such stations are available in the Lake Roosevelt area, would be useful to determine whether crustal adjustments are continuing today as they are in the Great Lakes and other areas of the world that experienced major glaciation. For reasons given later, we suspect that few, if any, elevation changes due to isostatic rebound are occurring today. Sufficient time has elapsed since the early land surveys so that recent elevation changes should be detectable and would reaffirm or deny at least one of these assumptions concerning terrace correlations.

Terrace levels reflect the tendency of lakes to fill towards their surfaces but cannot be used in the precise way that strandlines can. One can only say that a former lake surface is somewhere above the level of the highest lake sediments preserved today. Thus, some of the variation in terrace elevation could be due to sedimentation differences in a given lake plus any crustal elevation changes that may occur. The range of elevations allowed for each terrace unit is apparently adequate in most cases to incorporate sedimentaiton differences and isostatic adjustments. We suspect that these combined influences do not exceed one or two contour intervals (one contour interval = 40 feet, 12 m).

The apparently small amount of crustal change in the Lake Roosevelt area is probably related to the rapidity with which the glacier advanced and retreated. If the interpretation of the absolute ages reported by Clague and others (1980) is correct, then the Columbia lobe crossed the international boundary about 17,000 years ago, maintained its near maximum position between about 15,000 to 13,000 years ago, and retreated back to Canada by about 12,000 years ago. The approximately 2000 years of maximum ice thickness may not have been great enough to develop mantle changes to trigger a significant long-term crustal uplift history. Much of the elastic component of crustal depression was apparently relieved rapidly during deglaciation before glacial lakes were filled with sediment. Thus, the upvalley terrace elevations do not reflect much, if any, isostatic uplift.

Geographic Location

The geographic location of a terrace along the reservoir puts certain limitations and expectations of events to affect sedimentation in the landform. Thus, knowledge of ice position and location puts time and genetic limitations on terrace elements. Ice marginal surfaces are well above reservoir level except near the glacial snout. Sediments in these ice marginal deposits can range from silt through gravels, depending on whether a temporary lake is created or if higher energy fluvial processes occur. Near the snout, fluvial processes dominate and surfaces grade down to lake level. Thus, the remnants of the ice marginal terrace here do not mark a higher terrace controlled by a high downvalley base level but are the result of localized glaciofluvial processes. Steepening of these fluvial surfaces increases as one approaches the glacier terminus as is true near the Castle Rock and Brush Creek ice positions. As the ice retreated, the lacustrine facies would advance up the valley in the wake of the retreating ice. Thus, the sediments would become progressively younger upvalley.

Lake Missoula floods deposited mostly sandy sediment onto the aggrading terrace surfaces. The thickness of the flood units increases in an upvalley direction where higher energy flood currents and a greater abundance of sediment produced flood bars. Thus, these flood surfaces are not closely related in elevation to lacustrine terraces. For example, in the Ft. Spokane area along the Spokane River valley, the 1440-foot (439 m) left bank terrace (SE ¼ Section 15, T28N, R36E) is equivalent to the 1560-foot (476 m) terrace on the opposite bank except that the right bank terrace has a pendant bar on top that accounts for the higher elevation.

Some of the lower terraces with gravel caps along the Spokane River and Columbia River valleys could be due to normal fluvial conditions during episodes of lowering base level or could perhaps be due to smaller Lake Missoula floods or lower volume flows in the last phases of a larger jokulhlaup. Flood bars at reservoir level near the Keller Ferry indicate that late flood events occurred.

Tributary streams flowing onto the terrace remnants form alluvial fans and increases the elevation of a terrace. Also, slope wash can increase terrace elevations near the valley walls.

Detailed Stratigraphy

Not enough time was available to adequately measure and describe the numerous stratigraphic sections exposed along the reservoir to see if distinctive features or characteristics could be used to equate one section with another. A complicated section with a good exposure requires about 4 hours of field time for two people to complete. That time could probably be cut in half as more sections are measured. Considering the hundreds of sections available and the amount of detail available in each section, a very rapid method of cataloging the nature of the bank material using 8x10-inch black and white enlargements and sketching the stratigraphy onto a clear plastic overlay was used. In most cases photographs taken from water level were used because of the better control of scale, lighting, and camera location. The photostratigraphy method was developed during the summer of 1985 so that the stratigraphy had to be done on Polaroid photographs at the same time that the black and white photographs were taken. The Polaroid photographs were used as field sheets on which the stratigraphy was initially drawn. Final stratigraphy drawing was done in the office rather than in the field which produces some inaccuracies.

The best possibilities for using stratigraphy for correlation of terraces are to use catastrophic flood deposits that are interbedded with varved sediments or to perfect techniques that used the paleomagnetic record in the sediments. If individual flood units could be widely correlated, then the associated varves could be used to develop an absolute dating system. Additional detailed studies of stratigraphic sections, particularly the varves, is especially desirable. Such a study would produce valuable detailed information on the physical character of the sedimentary materials at specific sites along the reservoir and the varve counts might enable better correlation of sedimentary units to be made. Time separations between floods might be distinctive and might be used for long distance correlation.

Datable Material

Of potentially key importance in correlation of terraces is to have absolute dates available. However, very few volcanic ash layers were discovered during the course of our reservoir investigations and no organic material was collected. New exposures are created annually and the value of even one find is very high.

Of the few ash samples identified so far, four are particularly useful in providing limiting dates on terraces and other Pleistocene features and events in the Lake Roosevelt area.

The 13,000-year old Mt. St. Helens set S ash collected in 1979 from the Elmer City gravel pit established that at least part of the 1700-foot (519 m) Nespelem terrace is of that age. Atwater (1986) collected wood from the same terrace in the lower San Poil River valley that produced a radiocarbon date of 14,490±290 years B.P. These dates help fix the age of the Castle Rock ice position and the Springdale moraine in the lower Colville Valley because both moraines are graded to the Nespelem terrace. Wood and pine needles collected from below the Mt. St. helens set S ash layer at Elmer City by Millikan (1981, p. 20) dates at 23,898±1040 which indicates that the Okanogan glacier reached this site after this time.

The discover of Glacier Peak ash deposited in lake sediments in the 1360-foot (414 m) terrace at Spring Canyon and the 1320-foot (400 m) terrace in the Turtle Lake quadrangle (SW ¼ Section 33, T28N, R37E) near Porcupine Bay indicates that Lake Columbia V existed as recently as 11,200 years ago. A similar ash collected in the lower Sanpoil River valley by Jerry Galin (telephone conversation, 1994) also substantiates our hypothesis that Lake Columbia persisted in very late Wisconsin time. Catastrophic floods in the Chelan reach of the Columbia River being studied by Stanley Gaugh (MS thesis in preparation, Eastern Washington University) might be produced by rapid drawing of a late stage Lake Columbia or perhaps by outburst floods from Canada descending the Okanogan valley.

Another possibility worth investigating is to attempt some radiocarbon dating of the winter (more carbon-rich) layer of varves. Such dates would determine whether the terrace sequence proposed here is correct (lower terraces are younger and are inset against the older terraces), it would enable a more accurate Pleistocene chronology to be established, and it would enable terraces to be more accurately correlated and dated along the entire reservoir. The University of Arizona recently acquired (about 1990) an AMS ^{14}C accelerator facility capable of dating small amounts of oranic materials. Pollen and plant microfossils from the organic-rich clay caps of varves could be dated with this state-of-the-art equipment.

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